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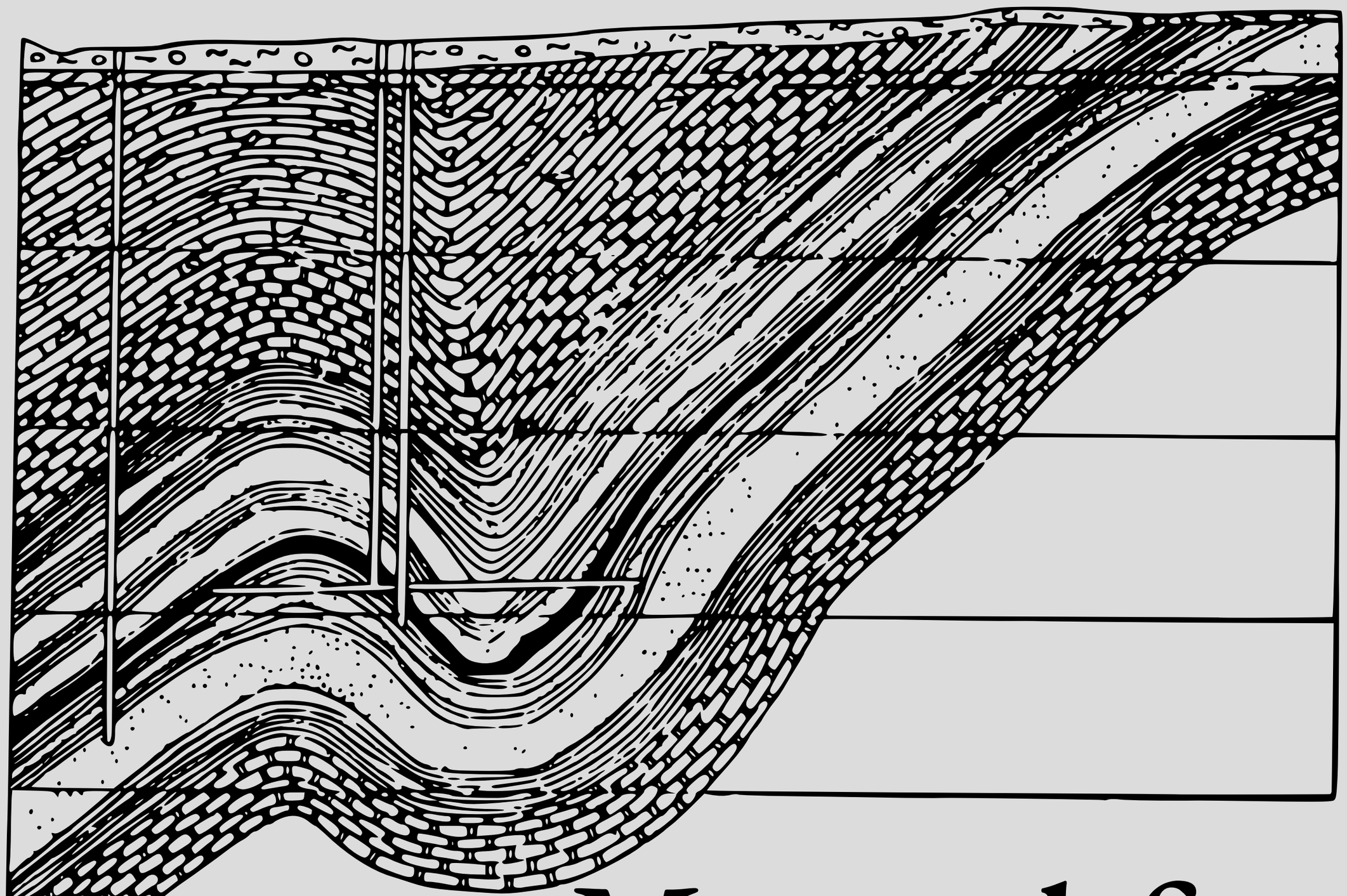

Manual for the Systematic Study of the Regime of Underground Waters

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MANUAL
FOR THE SYSTEMATIC STUDY OF THE REGIME OF UNDERGROUND WATERS

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PREFACE

The introduction of modern industrial methods into the intensively expanding agriculture of the Soviet Union has caused an active development in many other branches of knowledge. One such sphere, the detailed research of underground water regimes and the extensive utilization of these sources, covering the entire territory of the country, is indispensable for proper irrigation, land reclamation, construction of ponds and reservoirs, as well as for rural water supply. This is of particular importance in the arid south-eastern and southern regions.

In 1953 the Ministry of Geology and Conservation of Mineral Resources of the U.S.S.R. decided to set up a supplementary basic network of state hydrogeological stations in arid regions for the study of the regime of underground waters, with the issuance of annuaries by the central station of this network, containing factual data and surveys on the above theme for individual regions and branches of the national economy, to satisfy current requirements.

This has made it imperative to compile a comprehensive manual on the topic, especially because formerly published material has either become largely obsolete or is now extremely rare.

The All-Union Institute of Hydrology and Engineering Geology has therefore printed the present manual with the aim of presenting the principles of underground water processes as the natural result of individual stages in their historical development. Only such an approach will permit the use of this volume in the interests of the national economy.

Much attention has been given to present the topic comprehensively (water levels and discharge, temperatures and chemical composition).

The information contained herein is the result of conclusions drawn from scientific analyses of work conducted for a prolonged period at hydrogeological stations of the Ministry of Geology and Conservation of Mineral Resources of the U.S.S.R. We will add that some of the statements and conclusions are being published here for the first time and are intended for broad discussion among interested hydrogeologists. Among other things included is a classification of factors determining the regime of ground waters and their genetic types (types of origin).

The present work does not embrace underground water problems as pertaining to the design of various engineering structures, although quite a few of its recommendations may be of value for the purpose.

Nor are specific questions of underground waters occurring under unusual natural conditions dealt with, such as in karst areas or in regions subject to landslides, these being treated in other manuals undergoing preparation by the All-Union Institute of Hydrology and Engineering Geology.

Neither have any separate chapters been devoted to underground water behaviour as related to industrial and civil construction, nor to subterranean mineral waters intended for medical treatment; as to the former, available material is scarce, while the latter theme is being handled by a special net of hydrogeological stations of the U.S.S.R. Ministry of Public Health. Such stations would need a specifically written work.

Forecasts of underground water regimes have at present acquired particular significance and are being broadly developed by Soviet scientists, who have made many suggestions in this field. Wide use is being made of forecast methods recommended by G. N. Kamensky and based on underground variable-flow computations and the application of equations with finite differences. Methods of P. Y. Polubarinova-Kochina and N. N. Verigin are being used in individual cases of forecasting.

Assimilated and successfully practised by hydrogeologists is the scale-mo lelling method (electro-hydrodynamic

analogy developed by N. N. Pavlovsky in steady-flow calculations, and V. S. Lukyanov's hydraulic integrator for calculation of unsteady filtration).

Problems of forecasting underground water behaviour are not, however, specially treated in this manual, which limits itself to certain methods of applying the data needed in forecasting.

The manual is divided into four chapters. The first chapter—general theoretical problems—treats underground water and its behaviour as a natural historical process reflecting certain peculiarities attendant upon its development. This is of primary importance for basic regional hydrogeological stations in ensuring proper scientific organization of stationary (permanent) observations.

All are aware that the network of observation points of each hydrogeological station includes a system of regional posts for ascertaining the behaviour of underground water in individual natural-historical areas and another for its observation under the influence of various artificial factors. Correspondingly, the second chapter is arranged to include not only principal studies of subsurface waters from their regional aspects (artesian and ground waters and those in the permafrost zone), but also references to the influence of a number of artificial factors. Such a subdivision of the text bears, of course, a somewhat arbitrary character; it is hardly possible to treat natural ground water regimes independently of artificial factors, just as it is likewise impossible to draw a sharp dividing line between natural regional subsurface water regimes and those connected with definite national economic problems.

The third chapter deals with methods of field work in the study of underground water behaviour, while the fourth contains recommendations relative to the collection of field data and its subsequent treatment.

The manual is primarily intended for the personnel of basic hydrogeological stations engaged in long-term stationary investigations of the above-noted phenomena in their regional aspect, in close relation to definite national economic tasks.

Each hydrogeological station should keep the following principal aims in mind in the execution of its work:

a) the study of the formation and the regime of principal types of underground water occurring within the sphere of operation of the station, with the view to creating a scientific basis either for the rational utilization of such sources or for combating them;

b) the study of underground water balance;

c) development of methods for forecasting the behaviour of this water in accordance with requirements of the national economy and, finally,

d) the development of methods for effective control of the regime of underground waters.

All this should be closely coordinated with definite national economic interests of the region covered by the given hydrogeological station.

Accordingly, each station should--

a) continually and systematically modernize its observation posts and perfect their equipment;

b) supplement its activities by developing specific scientific and methodical problems, utilizing for this purpose, among other things, the results of observations obtained at experimental water-balance posts;

c) determine the natural conditions governing the behaviour of underground water, bearing in mind that hydrogeological stations provide one of the principal means of procuring new data necessary for the development of hydrogeology;

d) study various hydrogeological processes and seek to discover their physical causes determining the character and direction in which these processes are developing;

e) extend the network of regional observation points with a view to accumulating sufficient information for forecasts of underground water behaviour. This network should be arranged with due consideration to geological and hydrogeological conditions of the given region, climatic and soil zones, topography (watersheds and lowlands), vegetation (forests and clearings), lithology of water-bearing strata (pebble-beds, sands, sandy loams) and other local conditions. To save time and expenditure this work should be conducted jointly with meteorological and hydrological stations of the Hydrometeorological Service of the U.S.S.R. and

other permanent observation points under the jurisdiction of other ministries and departments;

f) extensively utilize the results of all studies for underground water control;

g) always remember that its basic task is the systematic introduction into the national economy of the results thus obtained;

h) study underground water balance by the method of finite differences, supplementing it by various investigations "in situ," with the purpose of direct exploration of all individual elements entering into the equation.

It should be noted finally that each hydrogeological station is under obligation to its own sharply delineated assignments which are to be regarded as its principal work.

The purpose of the present volume is to render scientific and methodological aid to hydrogeological stations in carrying out the duties assigned to them.

The manual has been compiled collectively by members of the staff of the All-Union Institute of Hydrogeology and Engineering Geology with the aid of scientists from other organizations (N. N. Bindeman of the "Vodgeo" Institute, and the late V. P. Sedov of the Frost Research Institute of the U.S.S.R. Academy of Sciences) and has been jointly edited by M. E. Altovsky and A. A. Konoplyantsev.

CHAPTER I

GENERAL PRINCIPLES

1. BRIEF REVIEW OF THE STUDY OF UNDERGROUND WATER REGIMES

Episodic investigations of underground water, dating as far back as the end of the 19th and the beginning of the 20th centuries, have established that the ground water table as well as spring discharges are directly related to precipitation, evaporation, moisture deficit, temperature, atmospheric pressure, and level fluctuations of adjacent streams and basins. An understanding of the regime of underground water was then very limited, having been confined to a study of level variations conditioned by the above-mentioned factors, but without consideration of methods of mathematical analysis.

Later studies developed along three principal lines:

1) mathematical analysis of water table fluctuations based upon the theory of unsteady flow;

2) laboratory experiments of individual ground water phenomena and observations of separate processes of such behaviour at experimental field installations;

3) development of a permanent network of observation posts intended for long-term study of underground water levels, discharges, temperatures and chemical composition.

The fundamental differential equation for unsteady flow of underground waters was deduced by Boussinesq in 1877.

Several particular problems within the framework of the theory of unsteady flow were proposed by Maillex in 1903, Forchheimer in 1919 and later by Felber (1931, 1932).

The principles for the modern theory of the movement of underground waters were laid down by Soviet scientists,

Academicians N. E. Zhukovsky (1923), N. N. Pavlovsky (1922) and L. S. Leibenzon (1934).

In 1940 G. N. Kamensky developed a theory of unsteady flow on the basis of the solution of a differential equation in finite differences. The method proposed by Kamensky permits the study of the underground water balance through mathematical analysis and also allows fluctuation forecasts of the water table to be made, embracing river hydrography, backwater due to hydraulic construction, infiltration of precipitates, and evaporation. In 1937 and 1939 V. S. Lukyanov developed a method of hydraulic analogies, permitting problems of unsteady flow of ground waters to be solved by use of hydraulic integrators.

A number of problems relating to subterranean unsteady flow were investigated by P. Y. Polubarinova-Kochina in 1949 and 1952 and N. N. Verigin in 1949, 1950 and 1952, who furnished a solution for the problem relating to obstruction of underground water along reservoir embankments.

In 1946 V. N. Shchelkachev investigated the volume elasticity regime of oil-field aquifers.

Forecasts and control of underground water are dealt with in separate articles published by G. N. Kamensky, M. A. Veviorovskaya, M. A. Shmidt, N. N. Bindeman and S. F. Averyanov.

In the field of unsteady flow Soviet scientists have laid the necessary theoretical foundations for a broad study of underground water balance and regime forecasts.

The development of methods for such a study and the summing up of factual field information are reflected by a number of authors.

P. V. Ototsky compiled a survey of the behaviour of ground waters in 1915-1916.

In Soviet times (1937) a collective work was published by M. A. Veviorovskaya, K. I. Razin and M. P. Semenov, dealing with methods in the study of ground water behaviour in regions of large-scale hydraulic and industrial construction. In 1938 under the joint authorship of G. N. Kamensky, N. N. Bindeman, M. A. Veviorovskaya and M. E. Altovsky, our knowledge in this field was summarized and further investigations outlined. A number of writers have

devoted themselves to methods in the study of ground water regimes and their balance in Central Asia. Among these are O. K. Lange (1934, 1935, 1939) and M. A. Shmidt (1940).

Some features of underground water regimes were looked into by means of special laboratory experiment.

The influence of precipitate infiltration, temperatures and atmospheric pressure on the water table was studied in experiments by P. V. Ototsky in 1915.

However, laboratory investigations have not been practised widely, since this method could only clarify certain individual aspects of the problem, quite isolated from the sum influence of natural and artificial factors that determine the behaviour of these underground sources.

Experiments have also included various field tests for the study of precipitation seepage, soil evaporation, etc. Of exceptional interest among these are large-scale experiments on condensation and water flow in the zone of aeration performed by A. F. Lebedev in 1936, and investigations carried out by A. A. Rode in 1935 and A. F. Slyadnev in 1941 and 1949. As compared with laboratory investigation this method yields more precise and authentic information. Combined with permanent observations, this tendency should be further encouraged.

But the principal method for the study of underground water regimes remains long-term investigations at hydrogeological stations of water levels, discharge, temperatures, chemical and gas composition and physical properties.

These not only permit a systematic study of regimes, but also serve to more precisely define and enrich our knowledge of natural hydrogeological processes.

The cornerstone of regular long-term observations of ground waters was laid by the Russian scientist V. V. Dokuchayev, who in 1892 sank a well in the Kamennaya Steppe with the aim of inquiring into the effect of tree growth on the replenishing of ground water. Dokuchayev realized that the transformation of nature in the arid steppes of Southern and Southeastern Russia would be quite impossible without intensive afforestation.

Observations at the Kamennaya Steppe station are being systematically continued even today. The results of these researches have fully justified the expectations of Dokucha-

yev: afforestation plays a positive role in the total balance of subsurface waters, that is, increases their reserves.

At the end of the past and the beginning of the current centuries investigations of ground water regimes were conducted at a number of points: in Tashkent (1874-1878), the Crimea (1891-1895), Veliky Anadol (1894-1901), Nezhin (1903-1912), Petersburg (1895), at the Timiryazev experimental forest station (1906) and the Odessa experimental field (1904), the Buzuluk woods (1911), at the Vasilevichy village of Minsk Region (1911), in the Golodnaya Steppe (1912-1917), and at the Mitishchi waterworks (1899-1911).

Permanent observations of underground water regimes have assumed large proportions only after the October Revolution. They have been carried out chiefly in the regions of Central Asia, where underground water plays a particularly urgent role in agriculture. Observations of from 2-3 to 5-6 years were conducted in the 1923-1931 period in the Ferghana Valley, the Samarkand Depression, at the Bukhara and Karakul oases, in Southern Khoresm, in Chirchik-Angren District, the Golodnaya Steppe, at the "Pakhta-Aral" experimental field, the Fedchenko Experimental Station and a number of other points. About the same time (1931-1932), the Scientific Research Institute of the Cotton-Growing Industry under the auspices of the Unified Hydrometeorological Service carried out some fixed observations in various parts of Central Asia and at experimental fields and stations. Observations of ground water behaviour were organized at a number of sites, usually for short terms (1-2 years) in conjunction with extensive hydrogeological investigations to substantiate new construction projects during the industrialization period of the country.

In 1931-1937 scattered observation points of the State Hydrological Institute served as a basic network for the study of ground water regimes ("regime stations"). In 1937-1938 this network was revised with the result that in 1938 it possessed 16 posts. At the close of 1939 the Chief Administration of the Hydrometeorological Service increased the number of operating stations to 39. Thus, the total number of observation points reached two thousands.

At present the study of ground water regimes on the territory of the Soviet Union is conducted by a basic state

system of several dozen stations operating under the supervision of the Ministry of Geology and Conservation of Mineral Resources of the U.S.S.R., as well as by many other observation systems under the directions of other ministries.

In irrigated regions of Central Asia and the Transcaucasus, research of ground waters is principally conducted by the Ministry of Agriculture of the U.S.S.R. and of water supply ministries of individual Soviet republics.

Mineral water regimes are studied by the Ministry of Public Health at principal health resorts of the Soviet Union.

Observations of ground waters are conducted in a lesser degree by the following ministries: Ministry of Electric Stations (in regions of hydraulic construction), the Ministries of Chemical Industry, Non-ferrous Metals and Coal Industry. The Academy of Sciences of the U.S.S.R. is conducting inquiries relative to ground water behaviour in permafrost regions. Of considerable magnitude is the study of subsurface sources in large forests, led by the Institute of Forestry within the framework of the Ministry of Timber Industry.

2. CONCEPT OF THE TERM "REGIME OF UNDERGROUND WATER"

With progress of knowledge in the field of hydrogeology the concept—"regime of underground water"—has, naturally, undergone substantial changes.

At the close of the 19th and beginning of the 20th centuries this term was understood to imply fluctuations of the subsurface water table caused by meteorological factors and variations in the level of rivers and other basins. But such a concept was extremely limited and could not embrace the entire gamut of changes that ground water was subject to in the course of time.

In 1938 G. N. Kamensky lent considerably broader meaning to "regime of ground water" by presenting it as a combination of phenomena associated with time changes (fluctuations in level, discharge and flow velocity, as well as changes in chemical composition and physical properties).

Such a definition clearly indicates that the regime includes not only fluctuations of the water table, but also all other changes of condition as affected by time, with particular emphasis on variations of discharge, velocity of flow, chemical composition and physical properties. This has considerably broadened our idea of the subject and stressed the necessity of studying the time changes of all its individual elements.

However, the above definition is still inadequate, since it does not reveal in full measure the sequence of natural processes.

Later (in 1947) G. N. Kamensky suggested a somewhat different definition, in which he stressed the influence of natural historical environments. According to Kamensky "the regime of underground water in its prolonged behaviour is governed by the influence of geological and climatic factors." But since it is subordinate not only to these, but also to soil and biogenic factors, this definition too is insufficient.

Furthermore, the regime could hardly be limited to behaviour or condition of the water, since "behaviour" does not convey any precise meaning, while "condition" characterizes only a certain static state. The processes of the regime are to be regarded as a sequence of changes, that is, these processes are to be considered as dynamic. Hence, the regime of underground water should be defined as a natural historical process, thus emphasizing the fact that the given phenomenon (regime) belongs to a more general category of natural occurrences.

A wide concept of the topic was presented by V. I. Vernadsky in 1934, although he did not treat the problem specifically nor formulate a definition of it as a special thesis. In dealing with the history of natural waters, Vernadsky presented a broad picture of their diverse changes occurring in the biosphere, stratosphere, metamorphic stratum and the magmasphere. He discussed the processes leading to physical and chemical changes of this water, as well as the various states of dynamic equilibrium existing between its numerous kinds and types and the particles of the solid, gaseous and biological spheres of the earth.

The regime of underground water is dependent upon a

number of natural and artificial factors (climatic, hydrological, geological, soil, biogenic and artificial), which affect it to a higher or lesser degree and change its properties in time and subterranean position.

All these natural and artificial prerequisites, without exception, are characterized by a more or less prolonged period of historical development. Moreover, interacting with other phenomena, they themselves undergo certain evolutions. Hence, their influence upon the regime of underground water is not constant, but continuously varies. The regime of underground water, therefore, presents a changing picture throughout the entire course of the earth's geological history.

Viewed from this historico-geological aspect, transformations in underground water (sequence of states and changes of properties) can be defined as processes of its formation. From this it follows that the regime in question can be considered as part of (or individual elements of) a more general process of water formation.

Seen in this light, investigations of individual elements of the regime (levels, velocity, discharges, temperature, etc.) are not ends in themselves, but only a means of studying ground water balance and the processes of its origin.

From the above the following definition may be formulated: the regime of underground water is a natural historical process representing individual stages of its formation and proceeding under the sum influence of interacting and changing factors (climatic, hydrological, geological, soil, biogenic and artificial).

3. INFLUENCE OF NATURAL AND ARTIFICIAL FACTORS ON THE REGIME OF GROUND WATERS

A detailed and complete study of underground water regimes necessitates a knowledge of natural and artificial factors changing its properties in time and position and requires the ability of distinguishing primary from secondary causes in all existing conditions, of disclosing the spe-

cific features contributing to the influence of these factors on the regime and, finally, of establishing quantitatively the relationship between individual properties of ground water and the prerequisites determining them. This will form the necessary basis for drawing up forecasts and reshaping underground water regimes as desired.

It is to be noted that while analyzing the data on hand, one should always take into account the diversity of natural and artificial causes and their combined influence upon individual elements of the phenomena. Therefore, when summing up information obtained through observations, it is of first importance to establish which factors are predominant in the given case, and which are of secondary significance and only introduce certain specific features into the problem and, finally, what is the physical nature of the influence exercised by individual factors. Only after this should a mathematical analysis of the given natural process be undertaken.

It must be emphasized that a purely quantitative description of the regime of underground water and its forecast are no longer sufficient today. Investigators must make wide use of the theory of unsteady flow and embrace the questions of hydraulics and thermal and chemical properties involved in the process.

A) PRINCIPLES OF FACTOR CLASSIFICATION FOR DETERMINING THE REGIME OF UNDERGROUND WATER

Factors influencing the regime of underground water are divided into two large groups—natural and artificial. The first was formerly understood as meteorological and hydrological; for these were of first importance when only the regime of free ground water was on the agenda, geological conditions having been taken into account only as corrective circumstances.

Inasmuch as the study of the regime should not be limited to phreatic water but must also include other types, the restriction of the natural group to only meteorological and hydrological factors is not sufficient.

Among natural prerequisites five genetic factors may

be distinguished: climatic, hydrological, geological, soil-forming and biogenic.

Since artificial factors are determined by man's deliberate economic activities, they should be classified in an entirely separate group.

Climatic and hydrological factors are conditioned by forces linked with solar energy; the group of geological factors incorporates those connected with the interior processes of the earth, conditions of sedimentation, geochemical processes, and the activities of geological agents; the soil-factor group embraces the soil-forming process, while biogenic activities are determined by the functions of living organisms.

Natural factors, differing genetically, exercise their own particular influences on underground water regimes. A brief description of these factors is given below. It is known that climatic factors are characterized by the kind of climate which is fairly stable for any given region of the globe. According to L. S. Berg, "climate" is "an average condition of diverse meteorological phenomena, inasmuch as this average condition influences the life of plants, animals and man and also determines the type of topsoil" (1938).

As distinct from climate, weather is not an average, but an actual condition of meteorological phenomena within a given period of time. In the opinion of Berg the concept of weather includes an element of variability and instability, while that of climate—an element of known constancy.

Types of climate influence the regime of underground water in a more or less stable manner (for the duration of the given type of climate). On the other hand, meteorological factors (weather), which are very inconstant and subject to periodic variations, cause rapid, and to a great degree, oscillating, changes in subsurface water regimes.

Also of great importance is the behaviour of surface streams and basins due to the close link existing between these and the subterranean hydrospheres. Rivers and lakes possess their own sufficiently stable regimes, since the conditions controlling their existence—climate, size of catchment basins, supply, etc.—change very slowly. Surface streams and basins vary in the course of their long-term regimes just as do their meteorological prerequisites.

The genetic group of hydrological factors, just as the climatic group, may also be subdivided into individual subgroups of slowly and rapidly changing factors, depending upon the duration of their influence on the regime of underground waters.

Slow-changing hydrological factors are analogous to climatic causes in their influence on the behaviour of underground waters, for, according to the pointed definition of A. I. Voeikov, rivers are "a product of climate."

Rapidly changing hydrological factors cause wavelike changes—fluctuations in underground water regimes which have their maximum, minimum and mean-variable time values. Such changes principally influence the hydrodynamic conditions of these sources and result in unsteady flow but do not change their genetic type, since climatic factors and geological agents created by the latter during comparatively short periods do not essentially affect geological conditions of the given territory.

Both climatic and hydrological factors principally influence free and perched ground water. In the case of deeper sources, climatic and hydrological factors are but of secondary significance.

In classifying periodic and amplitude fluctuations, N. N. Bindeman (*The Influence of Meteorological Factors on the Regime of Underground Waters*; 1938) creates a separate group: "Fluctuations of Geological Duration." The author points out that factors which give rise to this type of fluctuations may be: a) changes in the position of drainage bases of underground waters, b) tectonic movements and c) solution of rock and the reverse process of its cementation. The same writer stresses the fact that age-long fluctuations of the underground water level should be studied by methods of historic geology.

In a speech delivered at the Conference of the Hydrological Institute in 1938 B. L. Lichkov said: "Elucidation of the natural laws governing fluctuation of the water level at present, as well as during forthcoming years, inevitably forces us beyond the immediate moment and compels us to consider changes of water regimes in the historico-geological aspect. But there is actually no limit to this historical outlook and, whenever time changes of the water

regime are being discussed, one is forced to leave the present epoch and traverse the geological past."

Recommendations made by Bindeman, together with the views expressed by Lichkov, on the necessity of setting apart a separate group for changes in the regime of underground waters related to geological processes, are quite justified and again emphasize the necessity of effecting a still greater subdivision for the group of natural factors. The majority of geological factors will naturally be classified as slow-changing.

Geological processes whose duration is measured in geological time essentially change hydrogeological conditions and, finally, completely or partly, destroy old, and lead to the formation of new, genetic types of underground waters. Geological factors exercise their influence anywhere in the earth's crust where underground waters are present. The importance of these factors increases with depth, where they determine the physical and chemical conditions of the waters as well as their position and distribution.

Of major importance to the regime of underground waters are soil-forming processes, which exercise their influence over the intensity of replenishment of underground water and, particularly, over its chemical composition. For this reason it is advisable to include all soil-forming processes into a special group. These, like geological factors, should be classified as slow changing.

Soil solutions and perched and free ground water are all immediately affected by these factors, although there is no doubt that their influence extends considerably deeper into the earth's crust.

At present the significance of biogenic processes with regard to the composition of underground waters—and particularly microflora activity—is being revealed in an ever-increasing measure. Also of essential importance is transpiration caused by trees and grass as well as agricultural crops. Plant transpiration occurring during vegetation periods should be included in a subgroup of rapidly changing factors, while century-long transpiration of plant colonies distributed about the earth according to zonal laws should be incorporated in the slow changing subgroup.

Another feature to be noted, peculiar to natural forces of underground water regimes, is that a number of such phenomena and processes are of an episcdic nature. These take place in the course of very indefinite intervals and cause peaklike variations in the regime of underground waters for which no mean values can be established. This leads us to set apart, together with slowly and rapidly changing factors, a group of episodic elements from among the genetic groups exercising a certain influence over the regime. For example, heavy rainfall and thaws may be taken from among climatic factors, and earthquakes, volcanic eruptions, etc., from the geological group.

Rapidly changing climatic and hydrological factors are of special importance to the national economy.

Slowly changing forces are the basic features of underground water regimes for geologic periods, while quickly shifting factors result in oscillating and rather rapid changes (intervals of days, years and longer).

Artificial factors should be listed in an entirely separate group, since they arise from deliberate economic activities of man. As contrasted to natural causes, artificial forces usually have a greater effect over underground water regimes. Another feature is their localized action.

Artificial factors include: construction of reservoirs and irrigation systems, afforestation, pumping of subterranean waters either for supply or for the purpose of lowering the water table, drainage during land reclamation, etc.

B) INFLUENCE OF CLIMATIC FACTORS

Quickly varying climatic factors may be subdivided according to their curve length and range magnitude into daily, annual and multiple-year classifications.

Among multiple-year climatic periods the most common are those with durations of 3, 11, 35, 77, 110-120, 640 and 1,800-2,000 years. Rainy and dry periods of several hundred years each have been computed on the basis of the size of annual growth rings of gigantic sequoia trees in California, whose age exceeds 3,000 years. Warm and cold spells, disclosed by Milankovich as periodic changes in the amount of heat received by the earth in the course of 650,000 years,

should be included in the group of slow-changing climatic factors.

It should be borne in mind, however, that many investigators entertain well-founded doubts as to the reality of regular periodic changes. It should be noted moreover that some of the periods appear to be only derivatives of shorter intervals and, therefore, are not associated with the effects of any natural forces. Thus, for example, the 35-year Brückner period may be a mathematical derivative of 3- and 11-year periods and may, therefore, bear no relation to climatic changes. The Brückner periods are not quite of equal duration. Out of 65 such periods, actually only 13 have a duration of 35 years. The rest are characterized by periods of other length: six of them, for instance, have a duration of 20 years, while that of four others reach 50 years.

Variations of climate with an approximate periodic duration of 11 years are associated with periodic changes in the number of spots on the surface of the sun; these affect the intensity of solar radiation, temperature of the air, amount of precipitation and barometric pressure. Irregularities in the number of solar spots do not exercise an equal influence over climate in various parts of the globe. In a latitudinal zone covering the continents of the northern hemisphere the maximum of solar spots is coincident with a decrease in the amount of precipitation, a fall of temperature and a rise of barometric pressure. This zone includes a considerable part of Europe, the northern half of Asia and the greatest part of North America with the exception of a part of the Pacific coast. On the continents of the southern hemisphere, as well as in a part of eastern Asia and along the western coast of North America, the maximum of solar spots coincides, on the contrary, with an increase in the amount of precipitates.

Such approximately regular periodic changes of climate affect the regime of underground waters, with subsequent periodic fluctuations of their level over a number of years. This is clearly illustrated by the fluctuation curves of the water table in the Kamennaya Steppe (Fig. 1).

Annual fluctuations in the regime of underground waters are closely linked with the earth's climatic zones. In temperate regions, for example, there are two periods of rise in

the level of ground water during the year (spring and autumn) and two periods of fall (winter and summer).

Changes in air temperature are followed by definite changes in the regime of free ground water (in connection with their physical, chemical and hydrodynamic properties). Variations of air temperature primarily affect the temperature of free ground water. A rise in temperature brings with it a decrease in the volume of gases dissolved in the water, an increase of evaporation, and a subsequently larger salt concentration. Higher temperatures of underground

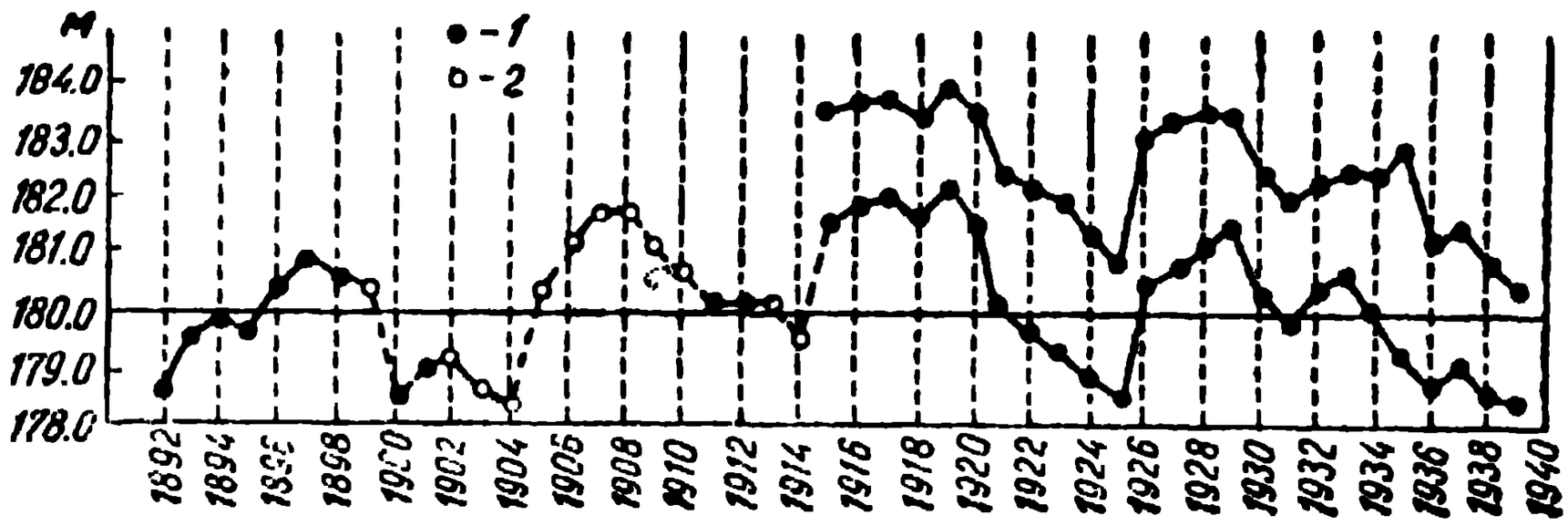

Fig. 1. Long-term fluctuation curves of ground water levels in wells Nos. 1 and 2 on the Kamennaya Stoppe plot, based on low water periods of the 1st of September (according to G. F. Basov).
1—actual measurements; *2*—probable levels.

waters lower their viscosity and result in speeded flow towards natural and artificial outlets, and a lessening of surface tension and thickness of the capillary zone. It should be remembered that variations in the ground water table caused by temperature fluctuations are quite insignificant in amplitude and commonly lie within the limits of accurate level measurements.

Most important in estimating the influence of air temperature on underground water regimes are yearly and daily temperature amplitudes, i.e., average variations of temperature of the warmest and coldest months and the warmest and the coldest hours of the day.

Amplitudes grow as the given latitude moves northward and as we move from the coastline towards the interior of the continents. A close proximity of large water masses (oceans, seas and large lakes) decreases the annual amplitude.

Daily variations of atmospheric pressure are quite insignificant and usually do not exceed 3-4 cm. by the water column. Furthermore, they are almost always obscured by general changes of atmospheric pressure. The greatest daily fluctuations of atmospheric pressure are observed in the tropics. With a drop in atmospheric pressure, underground waters loose some of their dissolved gases and with the existence of overlying impermeable beds their level changes but little.

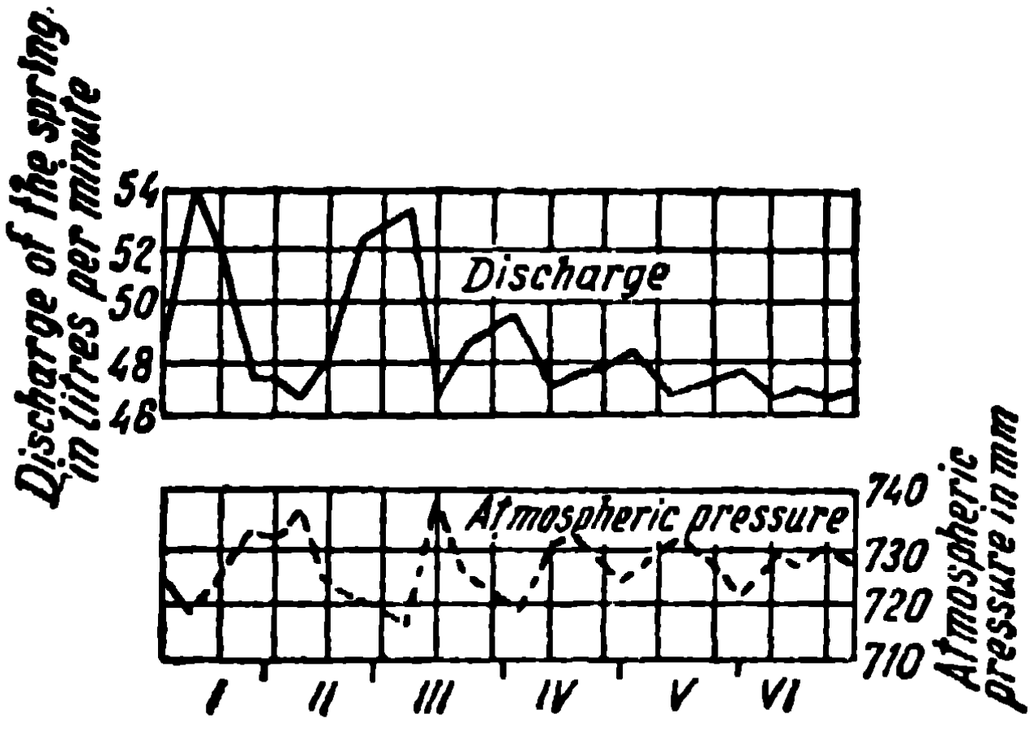

Fig. 2. Effect of atmospheric pressure on spring discharge at Karlovy Vary in 1927.

Meteorological elements may undergo considerable change within very short periods; heavy rainfall and thaws serve as good examples.

Such meteorological variations lead to sharp rises in the level of free ground waters or to changes in spring discharge. On corresponding diagrams this is illustrated by peak values not amenable to any mean classification.

Episodic changes of atmospheric pressure cause variations of discharge, level and, to a certain extent, quality of the water. This, however, occurs only when underground air is sealed from the atmosphere by air-tight strata. A well at Karlovy Vary is an interesting example of such a change of discharge (Fig. 2).

C) INFLUENCE OF HYDROLOGICAL FACTORS

Underground waters are closely interrelated with surface streams. During periods of high water, rivers very frequently serve to replenish underground sources, while, on the other hand, in periods of low water they are, in their turn, replenished by the latter. There exists a similar close relationship between underground waters and lakes, seas and oceans.

The bond between surface and subsurface waters is noted

primarily when fluctuations in the former are transferred with varying rapidity and degree to the latter and alter its level. Interflow of both waters naturally results in physical and chemical alterations of subterranean waters.

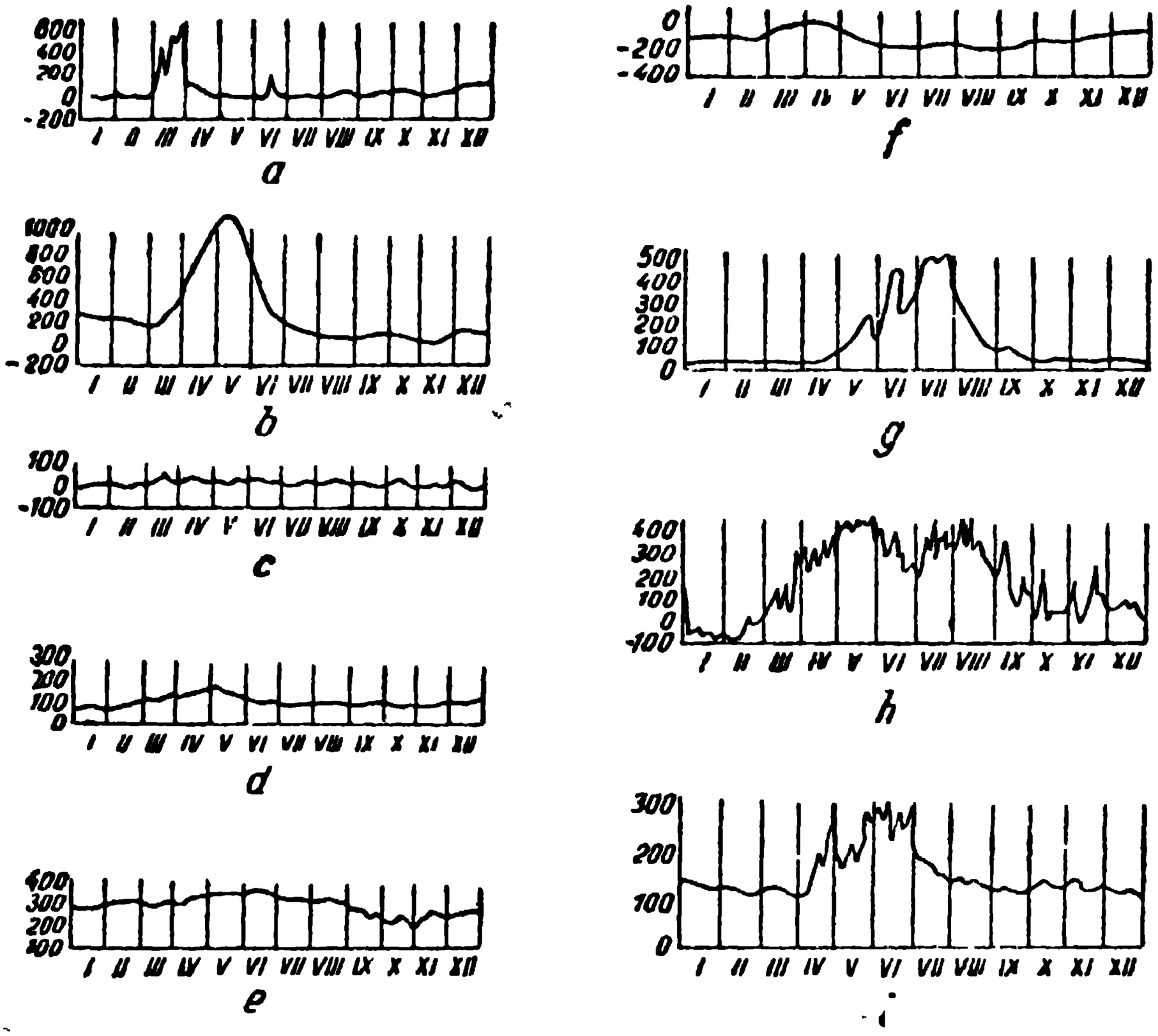

Fig. 3. Typical river hydrographs.

At present, best known is the relationship between river levels and subterranean water tables. Sharp fluctuations of river levels during high water and floods cause the rise of free ground water, the magnitude of which lessens with an increase of distance from the river bank.

The character of ground water fluctuations is of course closely associated with the annual regime of river levels. The latter varies greatly in accordance with a number of natural circumstances. In 1936 A. V. Ogievsky distinguished the following types in the level regimes of rivers:

1) Lowland rivers with small catchment basins (such as the Volga near the city of Kalinin), and sharply accentuated spring high water and probable flood waters due to heavy rainfall (Fig. 3, *a*).

2) Lowland rivers with large catchment basins (as the Volga near the city of Gorky and the Dnieper near Kiev) with considerable spring high water followed by its gradual fall and with the usual absence of sudden or considerable rises during the summer and autumn (Fig. 3, *b*).

3) Large lowland rivers in their lower courses (as the Volga near Dubovka and the Dnieper near Kakhovka) with a smooth curve to their low water periods and with medium spring high floods (Fig. 3, *c*).

4) Maritime sections of lowland rivers (North Dvina and the Dnieper near the city of Kherson) with level fluctuations caused by winds blowing to and from the sea as well as by the tides (Fig. 3, *d*).

5) Lake rivers with smooth spring high water and floods, such as the Volkhov and Svir (Fig. 3, *e*).

6) Swampy rivers with slow-changing levels such as the upper reaches of the Pripyat (Fig. 3, *f*).

7) Mountain rivers with small catchment basins taking their sources in glaciers and everlasting snowfields (Terek, Malka), and with highly accentuated daily level fluctuations and floods caused by heavy rains (Fig. 3, *g*).

8) Mountain rivers with small catchment basins whose sources are below the snow line, with low spring floods and catastrophic high water due to heavy rainfall such as the Katun (Fig. 3, *h*).

9) Mountain rivers with large catchment basins and very complicated regime curves such as the Kura (Fig. 3, *i*).

All these types of water level regimes in rivers are correspondingly reflected in the regimes of ground water hydraulically joined with rivers.

Similar to rivers, many lakes also have a close hydraulic link with underground waters, whose levels change when the lake levels fluctuate. Level variations in lakes are subordinate to climatic factors and very well reflect changes in the latter not only in the course of the year but for many years and even centuries. In the lakes of tropical countries, where the annual range of air temperature is

small and evaporation is therefore even, variations in water level depend principally upon the amount of precipitation and their annual distribution. Lake levels in the temperate zone are controlled by evaporation and precipitation; in the spring when the snow begins to melt at temperatures but little above zero and evaporation from the water is still insignificant, the water level in lakes reaches its maximum but drops in the summer due to considerable evaporation. The range of level fluctuations in lakes of the temperate zone is comparatively small.

Oceans and seas are likewise closely interrelated with underground waters, which drain into the sea bottom and at many points find their outlet in the form of such concentrated springs as to cause local areas of fresh sea water to appear. In rarer cases sea water penetrates within the mainland.

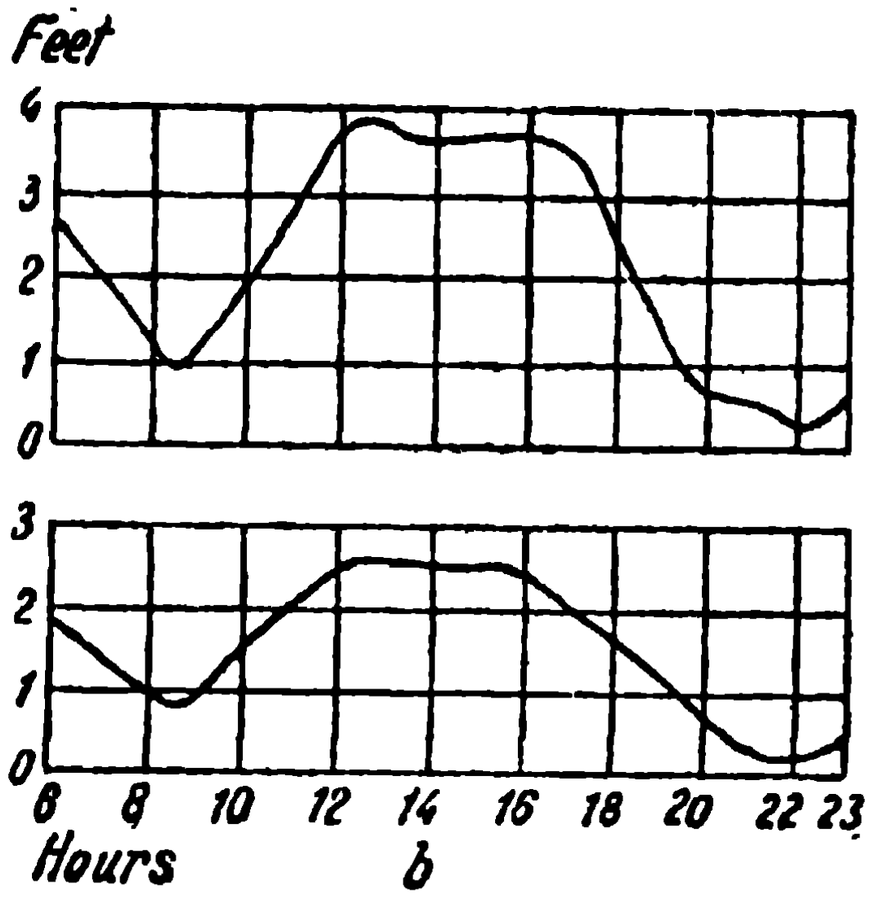

Fig. 4. Fluctuations in relation to tides (a well in New York).
a—tide; *b*—fluctuations of water level in the well.

The tide and sea surf exercise a predominant role over the regime of underground waters.

Tides have 12-hour periods (due to gravitational forces of the moon) and 24-hour periods (caused by similar forces of the sun). Twice a day the waters of the ocean rise, reach a certain maximum, and twice they fall. In the open sea, near islands, tidewater has the least rise, not exceeding one metre. Along coastlines with wide continental platforms, the tide reaches considerable heights. In the sea of Okhotsk it reaches eleven metres. The Mediterranean and Red seas have very low tides while the tides of inland seas are hardly to be marked at all. In the Black and Baltic seas they reach a height of about 7-15 cm.

Tidal phenomena call forth undulating alterations in the underground water level, which twice in the course of the day reaches its maximum, and twice falls to its daily minimum (Fig. 4).

In concluding this survey of climatic and hydrological factors which exercise their definite influence on underground water regimes, it should be noted that climatic factors have a wide effect, while the influence of hydrological forces is confined to comparatively small distances from river banks and sea and lake shores.

D) INFLUENCE OF GEOLOGICAL FACTORS

With the exception of earthquakes, volcanoes and landslides, which should be classified as episodic forces, the majority of geological factors are slow changing.

Such slow changing prerequisites include: processes of katamorphism, epeirogenetic movements, tectonic processes, terrestrial heat and gas saturation.

The combination of processes which change the rocky body in the upper part of the earth's crust is embraced under the general heading of *katamorphism*. Of major importance among these processes are weathering and cementation. Katamorphism takes place under conditions of moderate and low temperatures and low pressures and largely lead to decomposition of complex compounds into simpler combinations. These processes are very closely related to underground waters, particularly in regard to their chemical composition.

Oxidation and leaching processes in the weathering zone, due to the intensified action of oxygen and carbon dioxide, result, on the one hand, in rock solution (karst) and, on the other, in the saturation of underground waters with calcium and magnesium bicarbonates, ferric oxides, in rare cases with sulphates and chlorides of the same metals, and with salts of sodium and potassium, the calcium and magnesium carbonates precipitating from the solution. In deeper zones, not only precipitation of carbonates is to be noted but also of sulphates and even chlorides. This leads to the cementation of water-bearing rock by filling small interstices and crevices with the aforementioned salts.

Slow oscillation of considerable sections of the earth's crust, known as *epeirogenetic* movement, adds some of its own features to the regime of underground waters. This movement gradually changes the altitude of erosion bases of the hydrographic network and the depth of water in sea

basins, which causes corresponding evolutions in underground water regimes.

In regions of land uplift, due to the lowering of erosion bases, an intensified natural drainage sets in which leads to dewatering of the area and accelerated circulation of underground waters.

On the other hand, in regions of land subsidence the circulation of underground waters is retarded, the intensity of natural drainage declines, and the area becomes swamped. These same phenomena must also exercise their influence over the chemical composition of the water. In the first case they result in the decrease, and in the second in the increase, of water salinity.

Of immense importance to underground waters are *tectonic processes*. They determine the position and interrelation of the strata.

There are diverse forms in which tectonic processes develop in the earth's crust. But we will only consider those which are related to the most essential factors of underground water regimes. This refers primarily to dislocations which alter the site of strata—including water-bearing formations—and thus establish new underground space interrelationship among them.

Folding results in displacement and squeezing of underground waters into other geothermodynamic zones; in the upfold zones an intensified circulation and decreased water mineralization set in, while in the downfold zones these actions are reversed. If the processes of folding progress slowly, the resulting waters may have an extremely heterogeneous chemical composition, representing various stages of desalination of diverse types of these waters. Simultaneously with folding and under the influence of dynamic and thermal metamorphism, underground water is squeezed to the edges of the trough with consequent expulsion of almost all salts contained therein, which may bring about considerable changes in chemical properties.

The processes of folding are accompanied by disjunctive dislocations. Faults of various types disrupt not only the folds, but the table areas as well which sometimes lie hundreds of kilometres away from the fault zone. The presence of faults in the folding zone makes circulation of under-

ground waters more complicated and results in a still greater admixture of waters of various chemical compositions.

Faults in table-like areas or in zones of more ancient folds serve to create better conditions for deep circulation of underground waters, which then become thermal and are enriched with various chemical elements and gases.

Tectonic structure is of cardinal importance to underground water regimes. Strata, pervious and impervious to water, form synclases which serve to create basic conditions for the accumulation and circulation of artesian waters. The tectonic features of the given structure affect the total artesian supply, its distribution within. the artesian basin, and its circulation and drainage.

Of exclusive significance to underground water regimes is *terrestrial heat*. Heat received by the earth from the sun penetrates as far as the constant temperature zone. Beyond this, all underground waters are under the influence of terrestrial heat.

Terrestrial heat imparts a given temperature to underground waters, depending upon their depth, and thus affects their physical properties.

But the most essential effect of terrestrial heat is the slow evaporation of underground waters which radically changes their chemical composition by enlarging their concentration of salts and resulting in a transition from hydrocarbonate to sulphate waters, and of sulphate waters into chloride waters.

With a rise of temperature, water density increases and leads to a change of water level in the ratio of:

$$h_2 = h_1 \frac{1+\alpha_2 t_2}{1+\alpha_1 t_1}$$

where α_1 and α_2 are coefficients of expansion at temperatures t_1 and t_2; h_1 and h_2 are the elevations of the water level.

The *rotation of the earth* around its axis is known to create an acceleration of the deflecting force of moving particles which, in the northern hemisphere, is directed to the right, and in the southern—to the left. The value of this deflecting force at the equator is equal to zero and increases in proportion to the latitudinal sine of the given area.

The influence of this force upon the direction of bodies

increases with a decrease in their density. In the case of air the influence of this deflecting force is so great that the study of the movement of air masses is quite impossible without it being taken into consideration. For surface waters the effect of deflection is comparatively negligible. However, in the course of long periods the effect reveals itself quite distinctly; rivers of the northern hemisphere attain steep right banks caused by their being constantly washed out by the current deflected to the right.

Current velocity of underground water is thousands of times less than that of surface waters, but nevertheless the effect, measured in geological periods, reaches considerable proportions.

A cardinal point for the regime of underground waters is the degree of their *saturation with gases* of various origin (biochemical, atmospheric, chemical and radioactive). With changes in gas composition there appear corresponding vacillations in the hydraulic properties of underground water and this may even lead to the building up of a supplementary source of energy for its movement.

Chemically active gases (oxygen, carbon dioxide) considerably influence the chemical composition of underground waters, this chemical content being regulated by certain states of chemical equilibrium existing in the water.

The class of atmogenic gases usually include those in which the percentage of individual components is similar to that existing in the atmosphere. However, no account is taken of the fact that gases of atmospheric origin (nitrogen, oxygen, inert gases, carbon dioxide) are dissolved in the rain and carried into the ground in amounts corresponding to their partial pressure and degree of solubility. Thus, if in the case of the atmosphere there are 31 volumes of inert gases, 697 volumes of oxygen and 2,604 of nitrogen to each volume of carbon dioxide, then in rain water there are only 1.5 volumes of inert gases, 21 of oxygen and 39 of nitrogen to each volume of carbon dioxide. The amount of gases dissolved and their relative content in rain water is dependent upon air temperature. With a rise in temperature of rain water the relative percentage of nitrogen increases while that of oxygen and carbon dioxide declines.

The earth's crust in tropical lands receives relatively

more nitrogen than oxygen and carbon dioxide, as compared to the countries of the temperate zone.

The presence of radioactive substances in the earth's crust and the processes of their decay introduce their own features into the regime of underground waters.

Slow changing geological factors have already been dealt with. Of episodic geological factors the principal one to be considered is the *earthquake*. Precise instrumental recordings show that the earth is hardly ever in a state of seismic rest. According to Sieberg the annual number of earthquakes averages 10,000.

The most essential changes in the regime of underground waters occur in epicentral areas. Seismic factors change the hydrodynamic and resilient state, thermal regime and chemical composition of underground water and even the conditions of its occurrence. The formation and filling of crevices give rise to new, and disappearance of old, springs. Faults, shifts, changes in fissures, landslides and cave-ins must considerably alter hydrodynamic conditions of underground waters, whose conditions of occurrence and thermal regime are changed by the sinking of individual sections of the earth's surface. Considerable changes also occur as a result of the release of large quantities of heat during earthquakes. Joining and intermixing of various water-bearing strata lead to a change in the chemical composition of underground waters. The content of free gases in springs increases due to the "shaking" received by water-bearing strata during earthquakes.

Up to the present no special observations have been carried out relative to changes of underground water regimes under the influence of seismic factors. Some data illustrating such changes are given in Table 1.

The tremendous phenomena of *volcanism* undoubtedly give rise to substantial modifications in the regime of underground waters, which in some cases may result in the complete disappearance of existent, and the formation of new, types of subterranean waters.

Every volcanic eruption is attended by an immense escape of heat and introduction of new substances, which correspondingly effect the thermal regime and chemical composition of underground waters.

Table 1

Year	Region of earthquake	Recorded alterations in underground water regimes
1838	Valakh (in the downstream part of Danube)	Numerous cracks were formed in the alluvial valley of Dymbovitsy up to the river of Seret from which fountains gushed to a height of two metres.
1862	The mouth of the Selenga River in Southern Baikal (Buryat Depression)	Lowlands subsided over an area measuring 21 kilometres long and 9.5-15 km. wide. Water appeared everywhere, numerous springs gushed up, and, finally, Lake Baikal swept to the subsided part of the land and flooded it entirely. In many places springs fountained up. In the village of Kudara, between the village of Dubinino and the Segan Steppe, wooden covers of wells were violently heaved upward like corks escaping bottles. At some points fountains of warm water gushed to a height of six metres.
1861	Corinthia	A considerable portion of the shore line on the Bay of Corinthia was submerged; numerous cracks formed from which sand, muddy water and gases were ejected.
1819	India	The natural dam "Ullahbunt" ("God's Dam") was formed. In the district of Ran-Kag numerous cracks appeared from which huge quantities of sulphuric water and silt erupted during a period of three days. In the adjacent district of Buini, water gushed out of wells until all the surrounding territory was flooded to a depth of 1.8 and even three metres.
1930	Japan, Atami	A jet of boiling water and mud gushed up to a great height.
1929	Germab, Turkmen Soviet Socialist Republic	In the districts of Ashkhabad, Bakharden, Gheok-Tepin and others there occurred an increase in the discharge of springs issuing from proluvium deposits at Kopet-Dag. The increased discharge was observed for 2-3 years.

In some cases changes in the regime begin even before the actual eruption commences.

It has been observed in many localities that prior to the eruption the amount of water in wells and springs decreases considerably and sometimes disappears completely. In other localities new springs come up. Sometimes the water in springs shows marked variation of chemical composition and mechanical admixtures. Thus, before the disastrous eruption of Helungung on the island of Java the water in adjacent springs turned turbid and showed a white silt sediment. Considerable changes also take place in the regime of surface waters: sometimes streams diminish in size, disappear entirely or, conversely, augment their discharge; the sea retreats from the shore. For example, before the eruption of Vesuvius in 1775, the sea retreated rapidly from the shore. In other cases, prior to the eruption the heating of the soil was observed, resulting in a sudden and rapid melting of permanent snows on mountain peaks, as was observed in Kamchatka, Iceland and America.

Mud volcanoes, not associated with genuine ones and situated mostly in regions of large oil deposits, evidently also contribute to special features in the regime of underground waters, though for the present these features are not yet known.

E) INFLUENCE OF SOIL FACTORS

The formation of topsoil, or the beginning of world soil formation, dates back to the time when vegetation first appeared on weathered rock. Hence soil-forming processes have their own protracted soil-geological history.

This soil-forming process consists in the synthesis and subsequent destruction of organic matter. Soil science distinguishes the small or biological cycle from the large or geological cycle of matter. The small cycle reflects processes taking place within the topsoil, whereas the large reflects its relationship to other natural bodies surrounding it, particularly with underground and surface waters.

Soil factors that condition the regime of underground waters have, undoubtedly, many particular features, even

if only because their formation proceeds with considerable participation of organic life.

The regime of soil solutions is closely associated with that of subsoil ground water. Of the greatest consequence is the movement of soil moisture as well as the migration of mineral and organic matter.

In northern moderately warm and humid regions a part of the matter is washed out of the topsoil and conveyed down to phreatic waters. In southern arid regions these waters sometimes serve as a source of replenishment of the soil cover with various salts, which is particularly true of saliniferous soils.

In 1899 the founder of modern soil science V. V. Dokuchayev effected his well-known division of all soils according to a series of zonal, horizontal and vertical genetic types, each having its own characteristic features, including those related to the regime of soil solutions. In accordance with this viewpoint soils are divided into lowland and mountain types. Lowland soils are in their turn subdivided into flood-plain, boggy, podzol (ash-coloured), chernozem, desert-steppe, salini ferous (white and black alkali soils) and lateritic types.

Each of these types is distinguished by specific soil-forming processes and has its own peculiar relationship to ground water.

Thus, typical for boggy soils developing within the zone of surplus humidity is an accumulation of semi-decayed organic bodies in the form of peat, as well as by the presence of long-term restoration processes. Conditioned by anaerobic decomposition of organic substances, considerable quantities of methane and hydrogen sulphide are formed with simultaneous evolution of free nitrogen, hydrogen and phosphine. A rich accumulation of ferrous oxides may also be noted.

The podzol zone of soils is marked by a high moisture content and the washing out of mineral and organic matter to deeper-lying levels. Readily soluble salts are washed out first, followed by those with a lower degree of solubility, such as calcium and magnesium carbonates. The forest layer of fir needles, leaves, boughs, etc., is subject to a process of mouldering (fungus decomposition) with the formation

of crenic acid. With the passage of time, as the salts are washed out, soil solutions are enriched with hydrogen ions and acquire an acid reaction. At this juncture organic and mineral colloids pass from the gel state to that of sol and are carried down by soil solutions. With the further passage of time the relative content of insoluble silica in the upper portion of the soil increases, which then acquires a light-grey colour resembling that of ash.

Washed out soluble-colloidal ferric hydroxides, aluminium hydroxides and humificated substances, coming in contact at certain depth with bases, coagulate and become partially or fully fixed in the soil, forming an illuvial horizon. The rest of these substances is carried down still deeper and penetrates into the ground waters.

Throughout the year chernozems (black soils) are mostly in a "dry" state and their low moisture content makes the development of microbiological processes difficult. In this regard, organic substances (rapidly decaying grassy vegetation) have not enough time to become completely mineralized and to accumulate in the soil in the form of stable humin compounds (the humus content in a fertile humus soil reaches 10-12%). The absence of moisture complicates the leaching process. In steppe regions only readily soluble salts are carried away from the soil, while carbonates are retained in the humus horizon.

The desert-steppe type of soil formation is marked by three kinds of soil: chestnut, brown and gray.

The typical topography of regions with prevailing chestnut and brown soils consists of flat or slightly undulating plains with small depressions and hollows, all of which form a variegated microrelief. The latter factor plays a considerable role in the regime of soil solutions and free ground waters.

As compared with humus soils the chestnut types are characterized by a smaller humus content (3-5% on the average). The quantity of humus gradually decreases with depth without any sharp change peaks.

Due to limited amounts of atmospheric precipitates and considerable evaporation losses the soils of the desert steppe do not undergo any serious leaching process or redistribution of organic and mineral substances in their soil pro-

files. In chestnut soils, only readily soluble salts are carried down to lower levels, while calcium and magnesium carbonates accumulate in the humus horizon.

Brown soils differ from the chestnut brand by a still smaller humus content (not over 2-3%).

And finally, the total amount of humus in gray soils covering the plain areas of Central Asia and Transcaucasus does not exceed 1-2% and their processes of leaching are not pronounced.

The prevailing process occurring in soils of desert-steppe regions and having the greatest relation to free ground waters is intensive evaporation with the result that only readily soluble salts travel downwards, thus increasing the total mineralization of these waters in which sulphates and chlorides predominate.

The sum of all this is that the desert-steppe zone is noted for a predominance of saline soils whose principal representatives are: black and white alkali soils, and solodi soils.

The first type is met with principally in gray soils, while the second and the third—in chestnut and brown types.

Soils designated as black alkali are distinguished by the presence of various readily soluble salts in quantities obviously detrimental to normal development of crops.

Accumulation of salts may have been caused by the prevalence of maternal salinized stratum of marine origin, by the transportation of saline dust from seashores by the winds, and by salt accumulation in depressions through precipitation. The principal cause of soil-salting appears to be the presence of free ground water and evaporation from the capillary film. Salting commonly occurs when free ground water occurs at a depth of 1.5-3 metres.

After desalination the sodium saliniferous soils (chloride and sulphate) are transformed into white alkali soils. Under the latter are meant soils whose absorbing complex contains sodium, while the salinizing salts themselves are washed down to deeper levels.

Periodic cycles of desalination and salination result in the transformation of white alkali soils into black and vice versa. During rainy periods the upper washed portion

of the soil may turn into white alkali, while the underlying layer remains black alkali as before.

As the washing process progresses, the white alkali soils are transformed into solodi soils, which in their adsorption complex contain H-cations besides the cations Ca, Mg, Na. During their further evolution saliniferous soils may turn into gray, chestnut and other types of soil.

Lateritic soils are mostly prevalent in subtropical and tropical zones. On the territory of the U.S.S.R. they are found only in Abkhazia and Adjaria. Owing to much heat and abundant humidity their organic content becomes fully mineralized and only a negligible part turns to humus. Due to an abundance of precipitation the decomposed products of organic matter and mineral compounds are washed to deeper levels. In the upper soil horizons, however, accumulation of iron, aluminium and manganese hydroxides takes place. Thus in its relation to underground waters the soil-forming process peculiar to lateritic types of soil is to a certain degree similar to the process of podzol soil formation.

F) INFLUENCE OF BIOGENIC FACTORS

Biogenic factors include vegetation transpiration and biochemic activities of the microflora.

Vegetation absorbs a considerable amount of underground water and then exudes it into the atmosphere through its leaves.

The amount of water required for vegetation transpiration is determined by the transpiration factor, which represents the amount of moisture expended by plants to form one unit of dry organic substance.

The transpiration factor is in a large measure dependent upon meteorological conditions, that is, in dry weather it assumes higher values and in wet decreases. This is illustrated by the following figures obtained at the Bezenchuk experimental station (Table 2).

The transpiration factor is also affected by the moisture content of the soil. Data obtained by D. N. Pryanishnikov for oats are listed in Table 3.

Table 2

Types of plants	Transpiration coefficient	
	1911 (dry)	1915 (wet)
Wheat	628	316
Oats	655	293
Barley	618	288
Millet	443	198
Maize	437	160

Table 3

Soil moisture in percentage of total water capacity	Transpiration coefficient	
	without fertilizers	with fertilizers
40	402	334
60	483	372
80	505	409

Data obtained through observing the effect of transpiration on the regime of ground water are rather scarce.

In the case of trees interesting information was obtained by G. F. Basov in the Kamennaya Steppe where investigations were conducted in forest plantations arranged in belts of varying width.

Data thus secured showed that the ground water table beneath the forest belts rose in the springtime while in summer and autumn specific "depression cones" appeared, the presence of which is attributed to transpiration during the vegetation period (Fig. 5). In winter these cones were filled again. Interesting observations over the daily course of transpiration were conducted in lucerne fields of the Escalan valley (U.S.A.) from the 28th of August to the 8th of September, 1926. Before the lucerne was mowed (31st of August) a daily rise in the water table of approximately 3 cm. was noted throughout the night till morning, and an equal fall in the day and the evening. These smooth variations in the ground water table ceased after the lucerne had been cut on August 31st and there began a general rise of water level (Fig. 6).

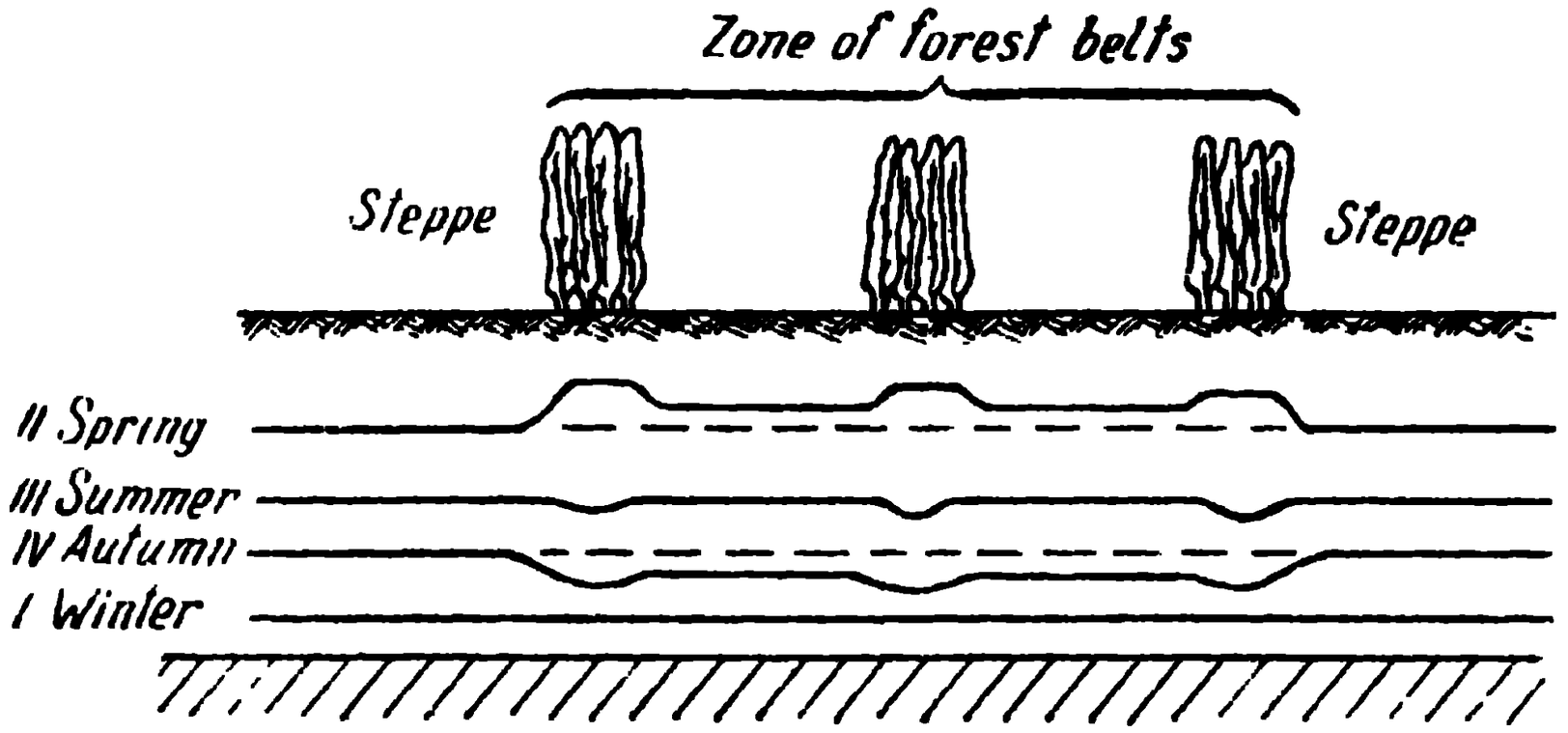

Fig. 5. Scheme of underground water levels during different seasons in the Kamennaya Steppe forest belts (according to G. F. Basov).

Biochemical processes in non-chlorophyll microflora are commonly subdivided into the following six types subordinate to the activities of various kinds of bacteria: nitrification, sulphurization, phosphorization, ferritization, desulphuration and denitrification.

The *nitrification process* results in decomposition of nitric substance with the evolution of ammonia. The latter, however, does not accumulate in the soil in any appreciable quantities, since other types of bacteria transform it into nitrites and sodium nitrates.

It should be noted that nitrification processes may also take place in anaerobic media.

The *sulphurization process* proceeds only in aerobic media and involves oxidation of hydrogen sulphide appearing as

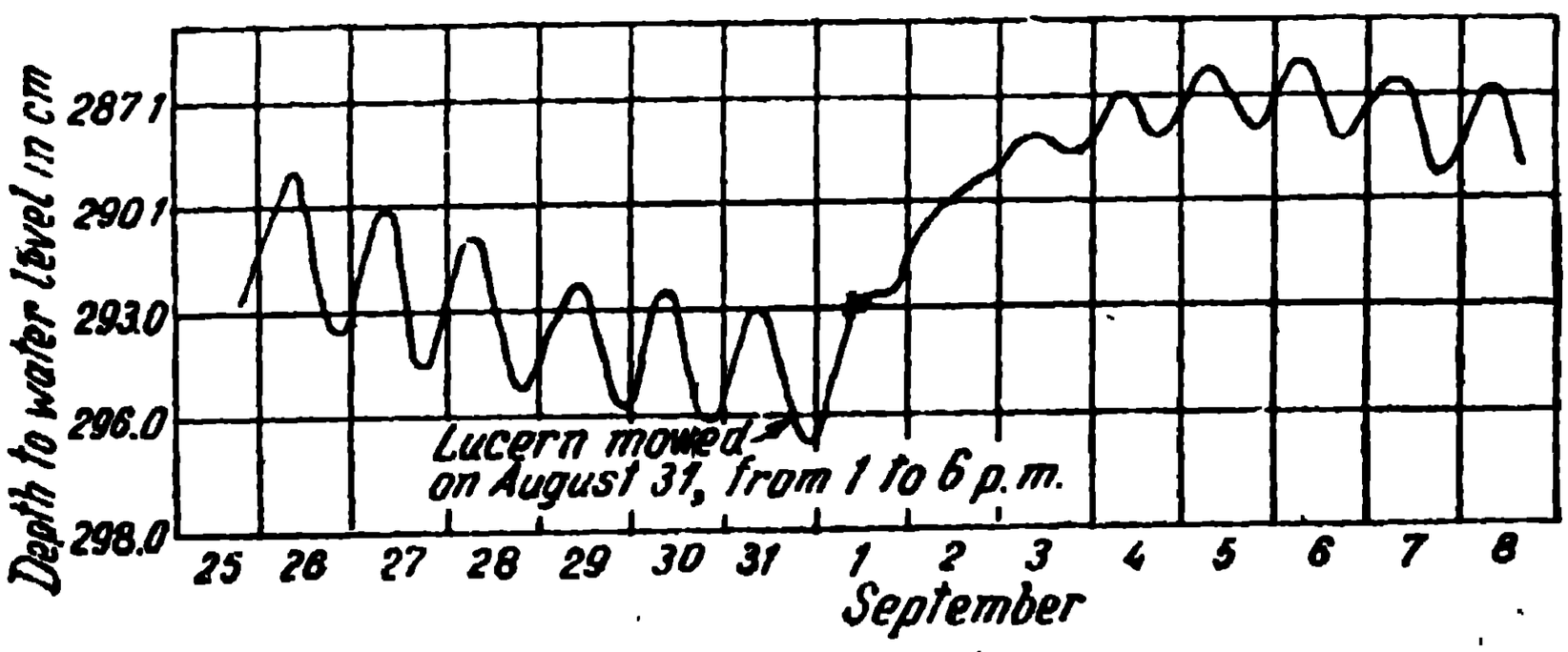
Depth to water level in cm
287.1
290.1
293.0
296.0
298.0
Lucern mowed on August 31, from 1 to 6 p.m.
25 26 27 28 29 30 31 1 2 3 4 5 6 7 8
September

Fig. 6. Daily fluctuations of ground water level in a lucerne field prior to and following mowing of the lucerne.

a result of decomposition of albumins by sulphur bacteria into sulphuric acid. Sulphur bacteria are found in many mineral springs.

The *phosphorization process* is affected by microorganisms during decomposition of organic matter in aerobic media. In anaerobic media reduction processes begin which result in the formation of phosphine with its subsequent expulsion from the soil through evaporation. Note should be made that phosphoric acid accumulates in the soil in other ways. Soil moisture partially decomposes insoluble calcium phosphates, and under the influence of acids the difficult soluble phosphatic compounds are transformed into the readily soluble.

The *ferritization process*, due to the effect of iron bacteria and air, causes the transformation of carbonates of iron into hydroxide. Iron bacteria are found in cold and hot springs and in saline waters.

The *desulphurization process* proceeds in anaerobic media and consists in reduction of the salts of sulphuric acid into hydrogen sulphide by a special species of bacteria (this process is sometimes called "hydrogen sulphide fermentation").

The same process was discovered in the oil and sulphuric waters of Apsheron Peninsula and in the mineral springs of Kraina.

There are indications that bacteria may penetrate to considerable depths. Thus, they are found in oil-field bores at a depth of 750 metres. The following conditions are required for this process: a) the presence of microbes of the proper type, b) an abundance of nutritive organic substances and c) anaerobic media.

The *denitrification process* is associated with the functioning of a specific kind of bacteria (denitrificators) and involves reduction of the salts of nitric acid with subsequent formation of simpler compounds such as nitrates, ammonia and free nitrogen. This process is not interrupted even in the presence of oxygen, but its progress is particularly intensive in the anaerobic media, when denitrificators use the oxygen contained in nitrates and nitrites.

G) INFLUENCE OF ARTIFICIAL FACTORS

The group of artificial factors is associated with the activities of man.

Depending upon the effect of engineering structures on the regime of underground water this group may be subdivided into four subgroups: drainage, watering, elastic and thermal factors.

The first subgroup includes temporary water-lowering installations, water intakes, various types of drainage plants and mine pumps.

The subgroup of watering factors includes hydraulic constructions (dams, canals), reservoirs, irrigation systems and their equipment, subterranean barrages, absorption wells, defects in water supply and sewers, and construction of foundations for industrial and engineering structures where the backing of ground water occurs.

As shown by V. N. Shchelkachev in 1948, changes in the elastic state of underground waters commence, for example, during the injection of water under high pressure into oil-fields to stimulate output, this being one of the factors of the second subgroup. In some cases, however, changes in water-head are not related to injection or pumping, but only to resilient undulation of the rocky strata due to the functioning of industrial plants or the passage of railway trains. Thus, twice a day during the passage of trains, automatic recording devices registered sharp changes in the water. level of a 60-metre artesian well situated at a distance of 35.1 metres from a railway line.

An example of a thermal subgroup factor is the construction of a heat-expending structure which causes changes in the regime of underground waters in permafrost regions.

Classification of factors relating to the regime of underground water is given in Table 4.

In conclusion it should be noted that when analyzing the data pertaining to underground water regimes, consideration must be given to the multitudiness of natural and artificial factors and their combined effect upon any single element of the regime. Therefore, when studying the material on hand the first thing to do is to establish which factors are predominant and which are secondary and only intro-

Table 4

Genetic factors	Groups of factors		
	slow changing	rapidly changing	episodic
Climatic	Types of climate	Seasonal meteorological factors (precipitation, evaporation, atmospheric pressure, air temperature).	Episodic meteorological factors (heavy rainfall, thaws, etc.).
Hydrological	Types of the regime of rivers lakes and seas	Spring floods, surf high and low tides, seiches.	High floods, fluctuations in water level caused by the action of the wind, ice clogging, jams and barriers.
Geological	Geologic structures Tectonic movements Terrestrial heat Earth kinematics Radioactive elements of rocky strata	—	Earthquakes. Volcanism. Mud volcanoes Landslides.
Soil	Types of soil-forming processes	—	—
Biogenic	Age-long transpiration of plant colonies	Seasonal vegetation transpiration.	
Artificial	—	Drainage, watering. elastic, thermal.	

duce certain peculiarities into the underground water regime. And, finally, what is the physical nature of the influence exercised by any of these factors. Only then should one begin the mathematical analysis of the natural process

under consideration, extensively applying the theory of unsteady flow of ground water, embracing the questions of hydraulics, thermal regimes and chemical composition of the water.

4. GENETIC TYPES OF UNDERGROUND WATER REGIMES

Classification of genetic types of underground water regimes has not yet been satisfactorily solved because of the absence of necessary data from different world zones. This manual, therefore, touches only on certain principles of classification of basic genetic types, which undoubtedly require further detailed study and a more precise definition.

Some of the published classification schemes represent classifications of factors, rather than types of regimes. In this connection reference should be made to the works of A. A. Kozyrev (1932) and M. P. Semenov (1937).

The classification scheme offered by Kozyrev indicates the following causes of fluctuations of underground water level:

a) fluctuations due to natural causes, subdivided into those associated with weather, those not associated with weather, and those related to surface waters and geological changes;

b) fluctuations resulting from human activities, and

c) fluctuations due to unidentified causes.

In the classification scheme presented by Semenov, all factors of any importance to underground water regimes fall under the heading of permanent, variable and artificial. Permanent factors include geological structure and contemporary topography, variable factors embrace climatic and hydrological categories, while the artificial classification comprises the influence of various engineering construction. In Semenov's classification emphasis is rightly laid on the subdivision of all factors according to their duration and the permanence of their effect upon the water regime. The setting apart of "permanent" factors, however, is not justified since all factors tend to change in the course of time. Moreover, the classification of Semenov does not take ac-

count of the fact that geological and climatic factors may be considered both as "permanent" and "variable." Thus, climate types appear to be fairly "permanent," while earthquakes should be counted among "variable" occurrences.

The classification of underground water according to fluctuations of level, suggested by O. K. Lange, is composed of the following groups: climatic, hydrological and anthropogenetic, with a subdivision of the first into two classes —pluvial and arid —of the second into "water-recharge and backwater," while the third group is divided into irrigation and municipal supply. In their turn, all classes are subdivided into series (simple, complex, smooth, interrupted, etc.) and the series into species, alike for all classes: stable, variable and unstable.

Not to mention a somewhat inadequate terminology found in this classification (particularly for series and species), we shall only remark that in the given case the author only classifies the annual curve of water table fluctuation, which at the present time could hardly be regarded as sufficient. Furthermore, this classification does not consider the regime of deeper lying ground waters. In analyzing the types of seasonal fluctuations of the ground water table on the territory of Uzbekistan, M. A. Shmidt came to the conclusion that their classification should be based upon factors causing changes in ground water sources and consequent variations in their level. In this regard Shmidt distinguishes the following types of seasonal fluctuations of the ground water table on the territory of Uzbekistan: climatic, hydrological, hydrogeological, complex (or mixed).

Some of the fluctuation types of ground water levels, classified by Shmidt, are shown in Fig. 7.

The listed classification schemes have a number of essential disadvantages. In the first place they take account only of phreatic water and leave entirely out of consideration those circulating at deeper levels. Furthermore, these classifications attempt to present typical charts for the fluctuation of the ground water level, evidently on the basis that only the graph may determine the factors influencing the regime of ground waters. This, nevertheless, cannot be acceded to. Thus, the graphs depicting the fluctuations of ground water level and marked by Shmidt as typical, may

be augmented by other similar curves which, however, would be dependent upon entirely different circumstances —such as a variable rate of pumping. And, finally, the clas-

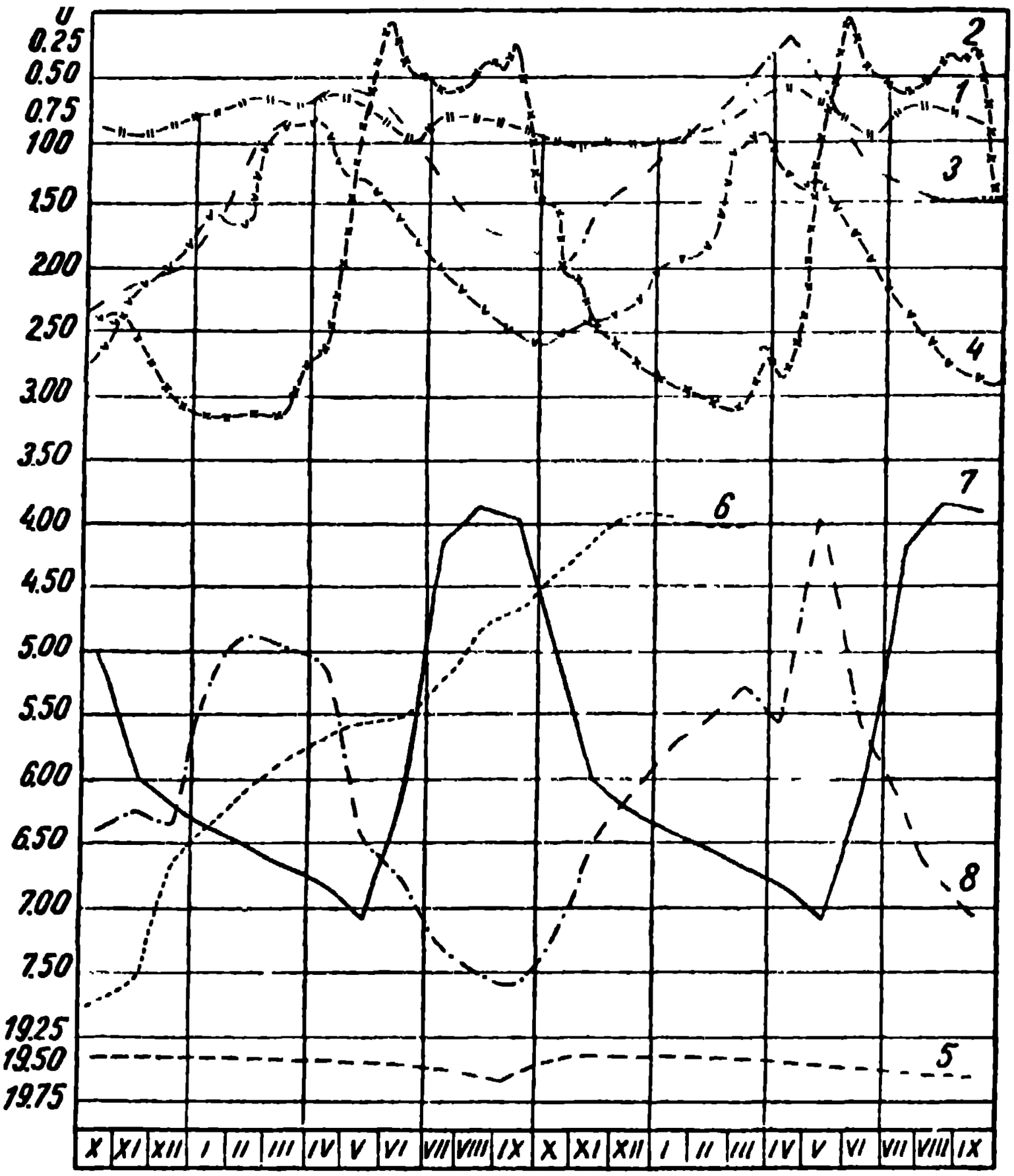

Fig. 7. Examples of level fluctuation curves.

1—feed from a permanently operating main channel in a desert climate zone; *2*—irrigated territories in a desert climate zone; 3—irrigated territory in desert climate zone with inadequate drainage and winter soil washing; *4*—feed due to precipitates and evaporation; *5*—"neutral" (desert) land; *6*—newly irrigated regions with inadequate natural drainage; *7*—feed from irrigation network with adequate drainage.

sification listed above covers only fluctuations of the water level.

Yet some of the proposed classification schemes contain some outstanding ideas which certainly should be considered during further development of this problem. The classification of factors of underground water regimes, suggested

by M. P. Semenov, rightly emphasizes the point that the relative stability of some of the factors is certainly of substantial importance for the regime as a whole.

In the classification of types of seasonal fluctuations worked out by Shmidt it is indicated quite correctly that any change in the source of free ground water would react simultaneously on corresponding fluctuations of their level. Therefore, the conditions incident to supply or replenishment of free ground water as well as its discharge should invariably be taken account of when classifying the types of the regime. And lastly, in all classifications the basic division of factors or types of the regime of ground water remains much the same: climatic, hydrological and artificial (or anthropogenic).

Taking hydrodynamic features as a basis, G. N. Kamensky in 1953 distinguished four principal regime types:

a) watershed type, formed by means of infiltration of precipitates, evaporation and underground flow, all of which are variable in time;

b) littoral and riverside types, determined principally by fluctuations in the level of rivers, lakes and seas;

c) piedmont and karst types, where, together with precipitate infiltration, a large influence over ground water regimes is exercised by the absorption of river water and, in general, surface run-off;

d) frozen-ground type, characterized by a complete or partial freezing of the water over the permafrost.

Kamensky's classification is of great scientific and practical interest inasmuch as it fundamentally distinguishes unquestionable types of the regime, each of which can be analyzed and prognosticated with the aid of equations for non-equilibrated flow of free ground water, proposed by Kamensky himself. This classification, however, cannot be regarded as complete, since it deals only with free ground water and, moreover, does not consider the regime of the latter in connection with its genesis and regional distribution.

The idea of genetic types of regimes is closely allied with that of genetic types of underground waters themselves. But these latter types are always linked with some definite field of distribution in the earth's crust. Hence the classification of genetic types of the regime of underground

waters must first of all take into consideration specific features of such distribution in the earth's crust.

Today hydrogeological literature is devoting special attention to the zoning of underground waters. It has been established that such diffusion is governed by certain fixed laws of zonation. This occurs both vertically (from the earth's surface into the earth's crust) and horizontally. These laws governing the zoning of underground waters should be taken as the basis for a classification of the genetic types of their regimes.

At present it would be difficult to state how many and just what types of vertical zones actually exist. We distinguish only two zones, which have been firmly fixed in the course of hydrogeological investigations, namely those of free ground water and deep pressure water.

At the same time it should not be forgotten that there are azonal ground waters which occur only under certain natural conditions and which cannot be incorporated, in accordance with their mode of distribution, into a more or less sharply defined zone. Thus, all types of underground water regimes related to hydrological factors (rivers, lakes and seas) are of local character since their formation is connected with surface streams and basins on the given section of the earth. Conversely, types of the regime conditioned by varieties of climate have undoubtedly a zonal distribution, since changes of climate are subject to the law of zonality.

Genetic types of underground water regimes should be distinguished according to their most prevalent or most important factor, possessing an all-round effect upon various properties of subsurface waters. Thus, for free ground water the conditions of their recharge play the greatest role, influencing not only fluctuations of the ground water table but also temperature and chemical composition. In rare cases only certain specific properties should be considered, as for example radioactivity of rocky stratum or a gas factor, etc.

We may now proceed to the question of genetic types of the regime of underground waters, bearing in mind to define them more precisely and in detail by means of their further subdivision.

Let us examine genetic types of the regime of free ground waters subject to the law of zonality. As mentioned above, the greatest influence upon the regime is exercised by types of climate or by climatic zones, which determine the most important conditions of recharge.

First of all there is the zone of arid climates, where the small amount of atmospheric precipitates is of the most essential significance, comprising 100-200 mm. per annum, and extremely high evaporation losses reaching 1,000 mm. and more per annum. The regime of ground water in arid regions, possessing a number of specific features, may be distinguished by its arid genetic type.

Then comes a wider zone, devoid of any regular snow cover or seasonal ground freezing. Here supply of ground water proceeds throughout the year by means of sparse precipitation and seasons of recharge coincide more or less with those of rainfall. This type may be designated as the "rainfall" genetic type.

Further north of this zone there is another of wide extension, characterized by regular snow covers and seasonal freezing of the ground. Replenishment of free ground water is here chiefly effected in the spring, both by melting of the snow as well as by seasonal transition of the moisture contained in the frozen ground from its solid to a liquid state. This type of origin of free ground water regimes could be referred to as the "snow-type."

Later, this type may be split into marine and continental types, with due reference to particular features of marine or continental climates; with seasonally frozen ground account must be taken of the fact that in a number of northern regions the melting of snow begins before the defrosting of the ground is complete. Consequently, melting snow in these regions would not be of any appreciable consequence to the feeding of free ground water.

The "permafrost" genetic type is especially singled out to cover the zone of the lithosphere with its eternally frozen ground and where the lower-than-zero temperatures introduce many peculiar features into the behaviour of underground water.

In northern latitudes and mountainous southern regions the recharge of free ground water is closely related to the

melting of glaciers which sometimes cover immense areas. The so-called glacier-type of the regime thus receives a separate classification.

For the regime of deep pressure (confined) waters with their huge adjustable storage capacities, less importance may be attached to annual fluctuations in supply and modifications in conditions of replenishment in various parts of the earth, than in the case of phreatic waters. For such waters velocity and degree of drainage are most essential factors which not only affect their hydrodynamic qualities but also their chemical composition and temperature. Their condition of movement and degree of drainage are, therefore, of considerable weight. Two zonal genetic types are established for these waters: "pressure-flow" and "pressure-nonflow." It is understood that "nonflow" is not to be taken literally since some movement does exist, but due to drainage difficulties the velocity of flow is extremely small. In most cases the first type is characterized by confined waters of the hydrocarbonate class, occurring at comparatively shallow depths and possessing a good water turnover and drainage. The second type includes deep, highly mineralized (sulphate and chloride) confined waters.

The necessity for establishing azonal genetic types of

Table 5

Hydrogeological zones	Groups of types of underground water regimes	
	zonal	azonal
Free ground water (phreatic water)	Glacial Permafrost Snow Rain Desert	River Lake Sea Karst Radioactive Artificial
Deep confined water	Pressure-flow Pressure-nonflow	Volcanic Geyser Gaseous Radioactive Artificial

regime both for unconfined and deep confined waters requires no special explanations, since these types have to do with the action of certain groups of factors already generally described in the foregoing section. Thus, azonal genetic types of the regime of ground waters (river, lake and maritime classes) are associated with the local action of one or the other types of hydrological factors. The group of azonal genetic types includes regimes related to special geological conditions: karst and radioactive types represent free ground waters of this sort while deep confined waters are represented by epeirogenetic, thermal (thermal springs), volcanic, geyser, gaseous and radioactive types. Both for free ground and deep confined waters an azonal, artificial type of regime is set up, which is directly related with the economic activities of man.

We conclude this chapter with Table 5 in which basic genetic types of the regime of underground waters are listed.

CHAPTER II

PRINCIPAL TASKS IN THE STUDY OF THE REGIME OF UNDERGROUND WATER

1. THE STUDY OF THE REGIME OF FREE GROUND WATER

A) General Principles

Since there is no widely accepted understanding of "free ground water" (phreatic water) in hydrogeological literature, the meaning of the term in our further presentation of the problem will be that of Nikitin, Savarensky, Kamensky and Lange: waters having a free (unconfined) upper limit, or water table, and occurring in the first impermeable stratum, or bed, from the ground surface. This also means that between the water-bearing stratum and the ground surface there is no confining impervious layer, with the possible exception of individual lenses, which sometimes may form a local head, and over which may appear so-called "perched" ground water. Recharge areas of free ground waters in most cases coincide with their distribution.

Free ground water contained in unconsolidated rock is designated as porous free ground water, while that related to hard and medium-hard rock is referred to as fissure free ground water.

This section will consider the principal questions relative to porous free ground waters. This will include such general problems as may come up during the operation of hydrogeological stations engaged in investigating ground water regimes.

Specific features of free ground water regimes in regard to reclamation, irrigation, afforestation, hydraulic construction, etc., are dealt with in sections 4-8 of the present chapter.

In fixed observations of the regime of free ground water the following points must be established:

1) conditions of recharge in various zones of distribution due to infiltration of atmospheric precipitates, con-

densation of moisture contained in the air, filtration of surface waters, as well as influx of water from other water-bearing strata;

2) conditions relative to drainage by springs, rivers, lakes, drainage installations, operating mines, as well as adjacent dry valleys and low basins (depressions) whose hypsometric level is below that of the ground water table;

3) direction and velocity of phreatic flow as well as the laws governing any variations there in time and subterranean position;

4) episodic, daily, seasonal, annual and longer variations in water table, discharge, temperature and chemical composition;

5) changes in bacterial and gas content (in individual cases);

6) the relationship between various elements of the regime of free ground waters, as well as their connection with basic natural factors causing alterations in individual elements of the regime (climatic, hydrological and others);

7) plots of seepage into the water-bearing strata under consideration of polluted river, lake, bog or industrial waste waters, as well as points of possible or ascertained "suction" of such waters, or of mineralized waters from other water-bearing strata into the operating or planned water intakes;

8) laws governing changes in the free ground water regime as effected by man's activities.

Furthermore, elucidation of the following points should be given the strictest and most serious attention:

a) geological structure, macro- and microrelief, and hydrogeological properties of the whole of the region under investigation;

b) areas of distribution of water-bearing layers (aquifers), as well as circumstances relating to their occurrence;

c) thickness, lithological and mineralogic-chemical composition, as wel las permeability of aquifers and their aeration zone, both horizontally and vertically;

d) thickness, chemical and granulometric composition of the soil;

e) character of the vegetative cover and its transpiration;

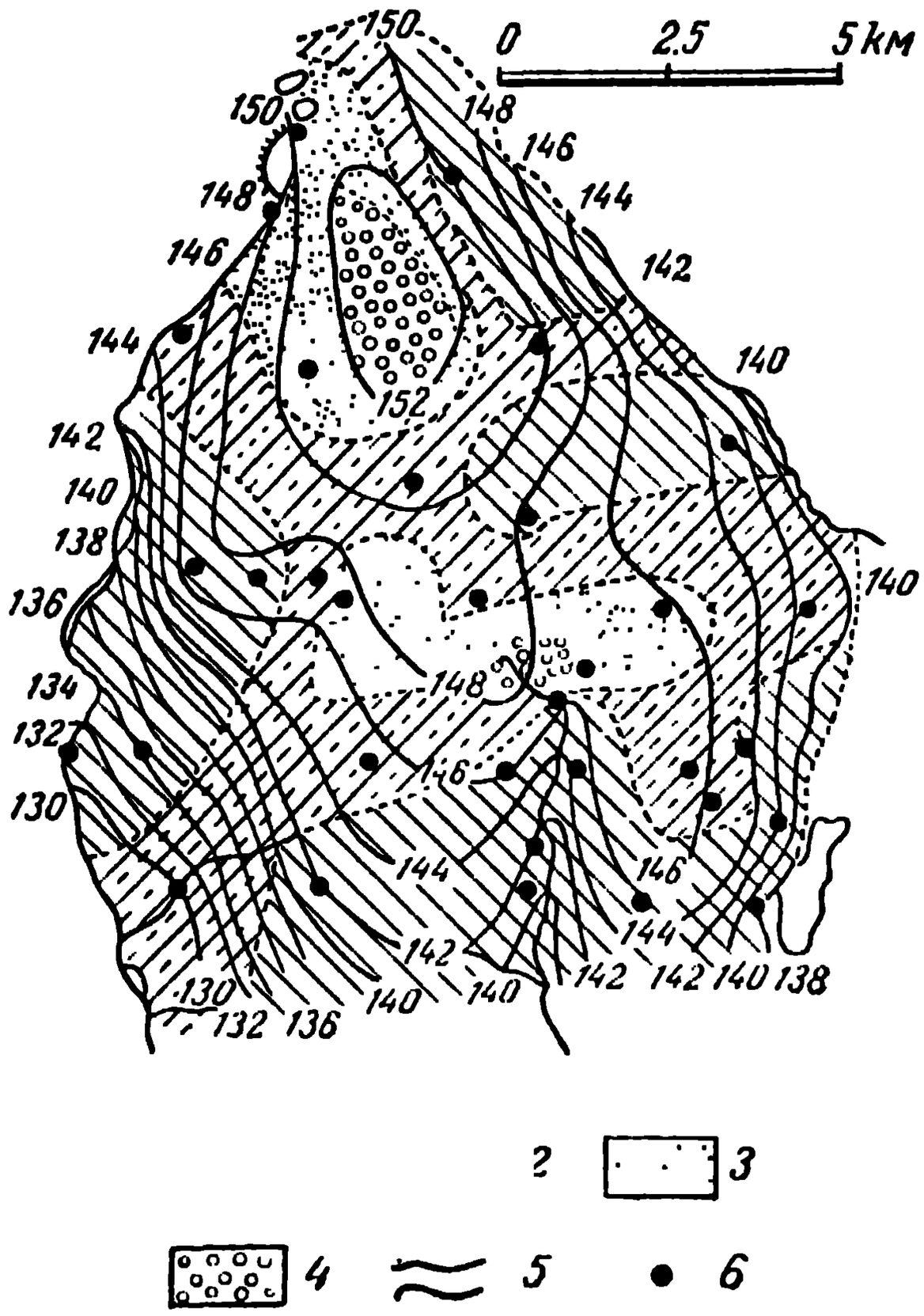

Fig. 8. A map of ground water contours and water permeability of rock (according to G. N. Kamensky and I. V. Garmonov).

1-4—areas with average permeability coefficients of water-bearing formations: *1*—from 3 to 10 metres daily; *2*—from 10 to 20 metres daily; *3*—from 20 to 30 metres daily; *4*—from 30 to 40 metres daily; *5*—water table contours at intervals of 1 metre; *6*—boreholes.

f) conditions pertaining to surface run-off;

g) moisture dynamics within the zone of aeration;

h) the nature of meteorological and hydrological factors and the influence of diverse measures such as irrigation, water-supply works, etc., on the regime of free ground waters.

The sum of all this data should serve as a basis for the establishment of the laws governing recharge, movement, drainage and quantitative and qualitative formation of the given free ground waters, as well as for disclosing the natural laws responsible for the development of the regime.

All-inclusive data regarding natural conditions of the given region and its ground water regime will contribute to proper forecasting of the latter and rational planning of all measures involved.

Investigation should begin with the collection of geological, hydrogeological and other information, and only then, and in some cases only after reconnaissance and prospecting of the given neighbourhood, or even after a complete hydrogeological survey, should planning of a stationary long-period observation network be commenced.

The next step is to draw up a map containing, besides the already-stated geological and hydrogeological material, the following plotted data:

1) meteorological stations and hydrometeorological points;

2) boreholes and wells for water supply;

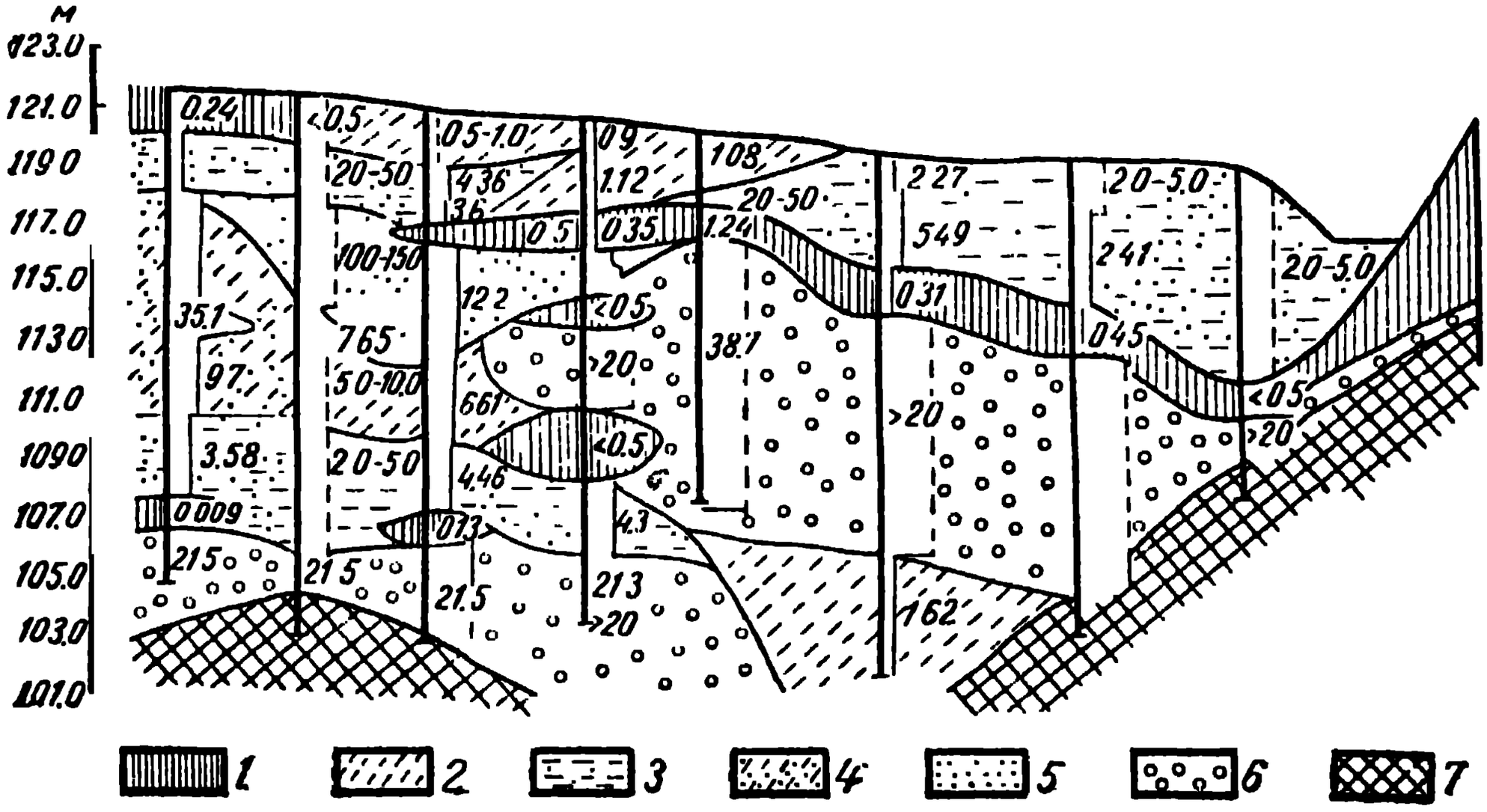

Fig. 9. Cross-section of water permeability of the rock (according to G. N. Kamensky).

1-6—coefficients of permeability: *1*—less than 0.50 metres daily; *2*—from 0.50 to 1.0 metre daily; *3*—from 1 to 5 metres daily; *4*—from 5 to 10 metres daily; *5*—from 10 to 15 metres daily; *6*—exceeding 15 metres daily; *7*—impervious bed.

3) shafts, galleries and quarries for extraction of building material;

4) dams, reservoirs, drainage lines, canals and other hydraulic structures;

5) disposal areas for sewage and industrial waste;

6) irrigated and drained areas;

7) contours of areas or places where observations are being effected by other institutions.

Geological and hydrogeological information thus gathered and summarized together with the maps are to serve as the basis for the following delineations:

a) a maximum number of geological and hydrogeological profiles in the direction of, and perpendicular to, ground water flow;

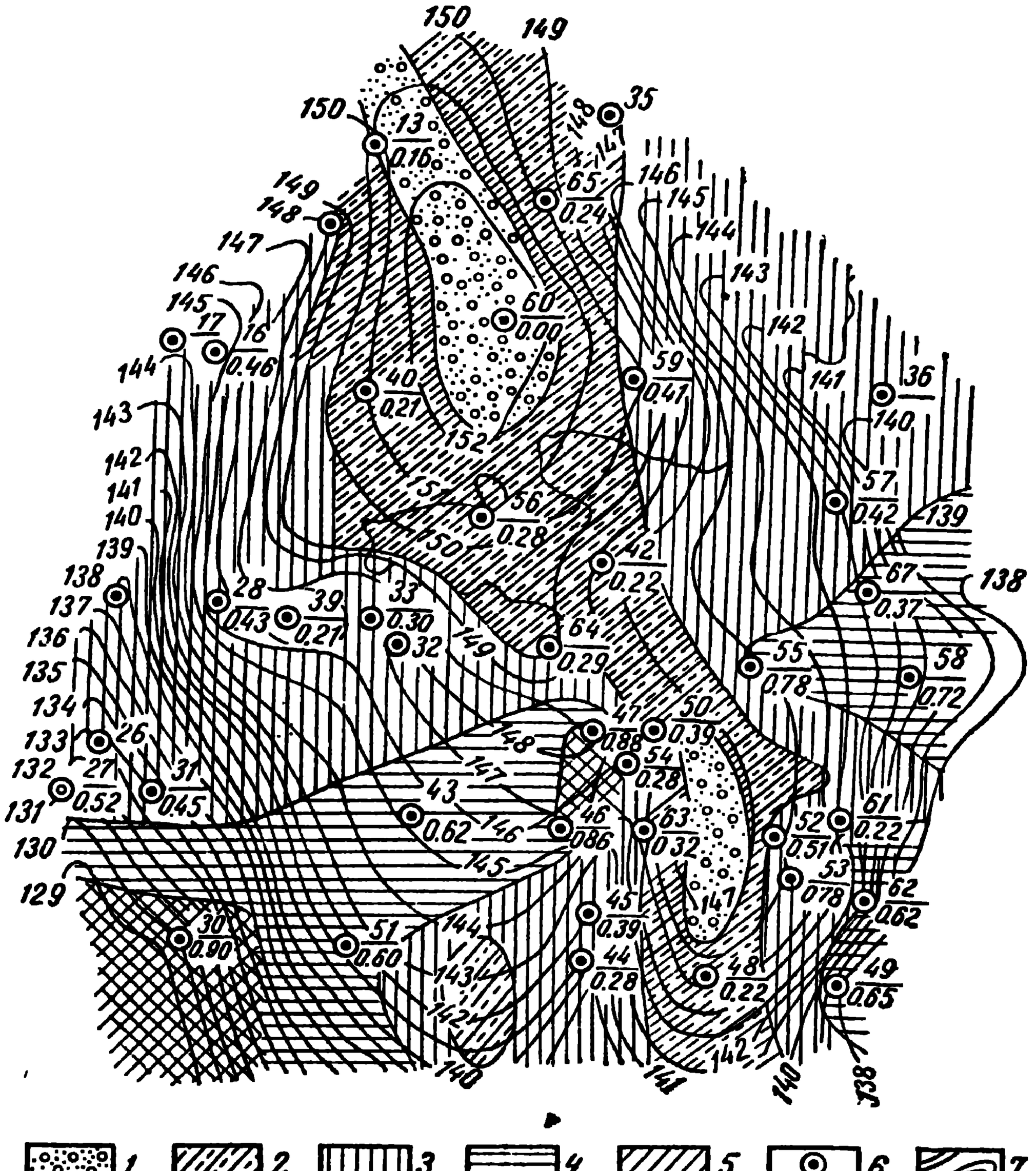

Fig. 10. A map of dynamic reserves of ground water (according to G. N. Kamensky).

1-5—rate of discharge of ground water flow per metre of breadth: *1*—from 0 to 0.20 m³ daily; *2*—from 0.20 to 0.40 m³ daily; *3*—from 0.40 to 0.60 m³ daily; *4*—from 0.60 to 0.80 m³ daily; *5*—exceeding 0.80 m³ daily; *6*—borehole: numerator—number of borehole, denominator—rate of discharge of ground water flow; *7*—contours of water table.

b) a map of water table and rock permeability contours of water-bearing layers (Fig. 8);

c) profiles of the water permeability of the strata (Fig. 9);

d) a map of dynamic sources of free ground waters (Fig. 10);

e) maps, illustrated in isolines, representing the depth of ground water for typical periods of the year;

f) a map illustrating chemical composition of the waters.

All this data will be needed for an adequate choice of observation sites and later for analyzing and coordinating information relative to the free ground water regime.

B) THE STUDY OF THE REGIME OF FREE GROUND WATERS IN RIVER VALLEYS AND WATERSHEDS

Free ground water usually flows beneath river and dry valleys filled with alluvial, alluvial-proluvial (piedmont) or fluvioglacial deposits. In river valleys this phreatic flow occurs in the terrace drift and flood-plain deposits and is closely interrelated both with the river and atmosphere. This hidden flow in the valleys may proceed towards, away from, or along the river course. Its movement along the river course takes the form of an alluvial underflow when flood-plain deposits of considerable thickness exist, and predominantly when the river has a considerable longitudinal pitch. Its course towards or away from the river may vary, depending upon the river's depth (low or high flood periods). The phreatic movement in dry valleys is commonly down their slopes.

Depending upon geological, hydrogeological or geomorphological conditions, recharge of free ground waters may occur either through river water infiltration (chiefly in the upper part of the valley), through water influx from some other water-bearing strata or through rainfall.

Recharge of the water table at the watershed depends upon the height of the impervious bed over the river's level. If the bed lies above the highest level, ground water is supplied by precipitates and condensation. If it lies permanently or periodically below the level of the river, the process is effected by precipitates, condensation and river waters.

In irrigated regions recharge of ground water is effected with a large participation of infiltrated water from irrigation systems.

Data collected as a result of many years of investigation has ascertained two distinctive types of free ground water regimes (according to G. N. Kamensky):

1) riverside type developed directly by the river and where meteorological factors are of secondary importance;

2) watershed type, where the river plays no part at all, but which is subject to meteorological factors.

Where phreatic flow has no direct hydraulic tie with the river, the first above-stated type does not, of course, occur.

A hydraulic link with a river takes place when an impermeable bed lies below the river surface (Fig. 11, *a* and *b*). Should this bed exist above high flood level, then there will be no connection of ground water with the river and the ground water regime will not depend upon that of the latter (Fig. 11, *c*).

There is an intermediate type of regime which occurs when hydraulic connection of free ground water flow with a river occurs only during periods of high flood (Fig. 11, *d*).

There may be three kinds of hydraulic correlation between surface and phreatic waters:

1) when during the greater part of the year the ground water table slopes towards the river (Fig. 11, *a*). The flow of unconfined water feeds into the river (the opposite is observed only during periods of high flood along a comparatively narrow strip of riverside). This chiefly prevails in regions where precipitation sharply exceeds evaporation losses and where conditions favourable to the formation of large streams of phreatic waters are created.

2) When during the whole of the year the subsurface water table slopes away from the river, i. e., when recharge of ground waters is effected largely through infiltration of river waters (Fig. 11, *b*). Such conditions predominate in regions with small precipitation and intensive evaporation.

3) When the ground water flow is directed along the river valley, resembling a subterranean branch of the river; this is mostly observed in valleys of mountain rivers.

In the case of hydraulic relationship between ground water flow and the river the regime of the former possesses the following features:

a) a change of river level is transmitted to the ground water and the table of the latter along the riverside experiences considerable instability, frequently amounting to as much as several metres;

b) during high flood the direction of flow, rate of discharge and sometimes the chemical composition of ground water along the riverside are subject to sharp irregularities;

c) during periods of high flood, when there is a marked difference in the temperature of river and phreatic waters, the temperature of the latter in the river zone is subject to variations. Such occurrences are observed especially in Siberian river valleys which are noted for their "island areas of permafrost" and subsequent deep winter freezing. Spring high waters, percolating into alluvial deposits and contributing to the thawing of the frozen ground, are cooled, mix with the ground water and lower its temperature. Conversely, during summer floods, underlying waters in individual sections of the valley may show a rise in temperature.

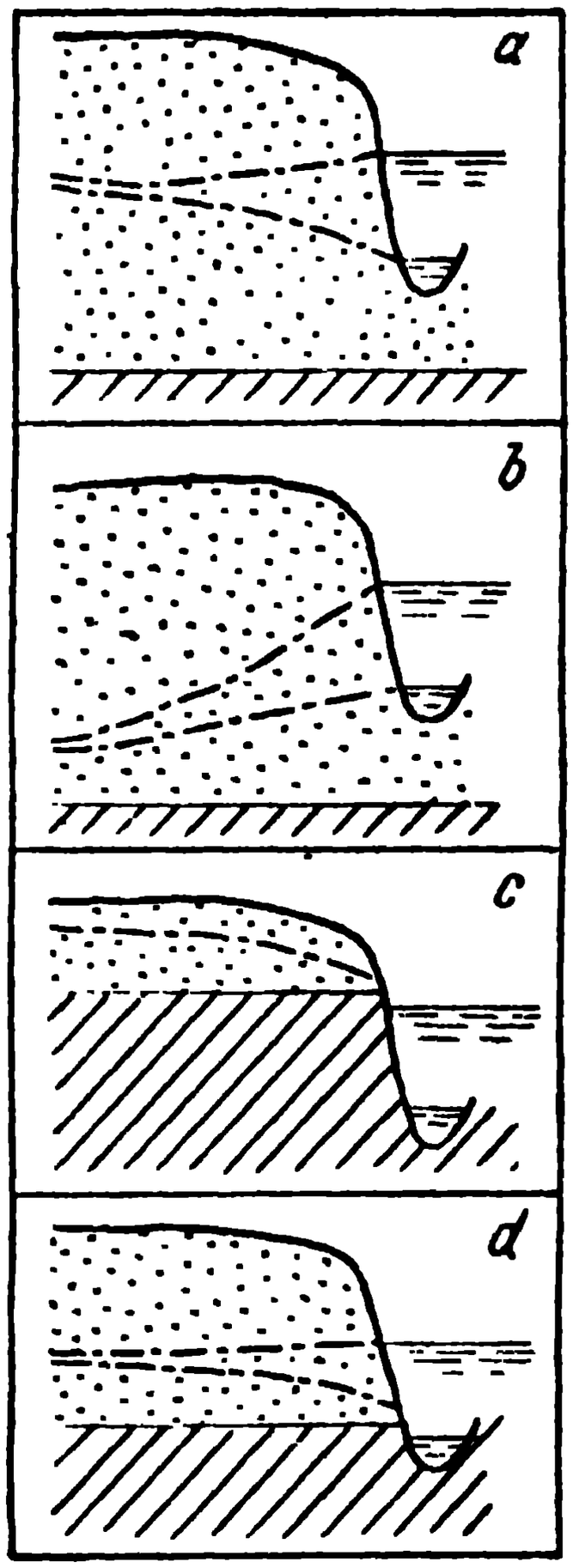

Fig. 11. Various relations between ground and surface waters (according to M. A. Veviorovskaya).

Level vacillations in rivers extend to ground waters to which such fluctuations are usually communicated for a distance of several hundred metres from the bank. Only when rises of long duration occur accompanied by considerable high flood amplitudes (in large rivers), do such fluctuations sometimes extend to a distance of several kilometres. With an increase in distance from the river the range

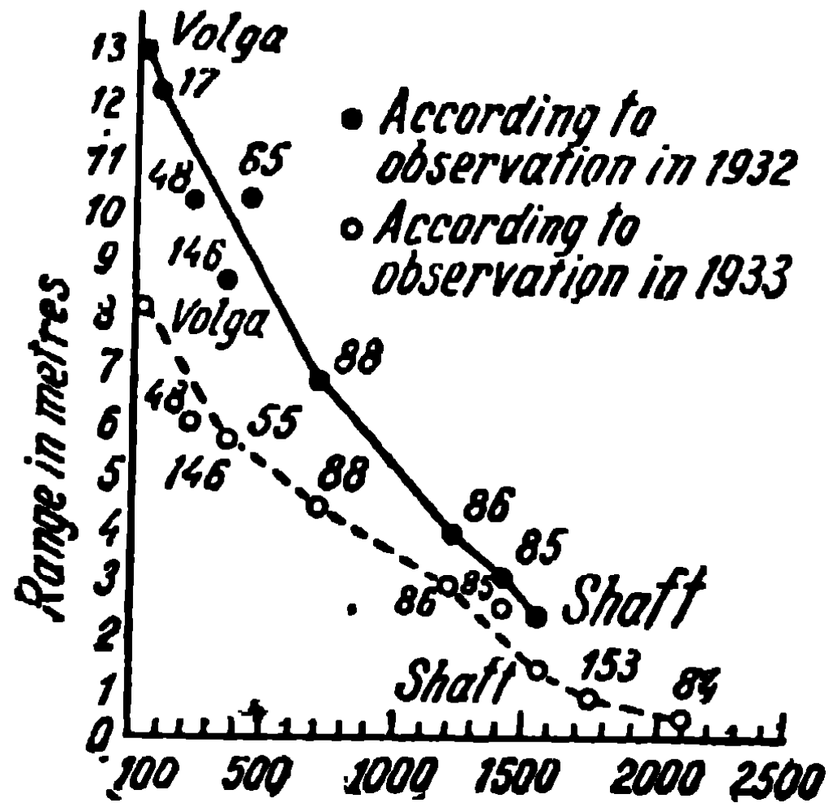

Fig. 12. Range of ground water level-rise as affected by spring high waters in the Volga River in 1932 and 1933.

of variation in ground water level declines, and the time-lag between maximum levels becomes more and more marked.

Fig. 12 illustrates the rising level curves of free ground waters at one section of the Volga valley (according to M. A. Veviorovskaya).

Irregularities of river level extend to ground waters at distances that increase with an increase in thickness and permeability of the water-bearing stratum and with a decrease in the water saturation deficit of the rock lying within the zone of saturation. Of particular significance is the effect exerted by rivers over ground water regimes when permeability of the upper portion of the water-bearing stratum is substantially inferior to that of the lower, since such a stratum in its hydraulic features becomes similar to that of the pressure type, and with a rise of the river the pressure head is rapidly transmitted along the water-bearing stratum.

During high flood in a river, together with the transfer of the pressure head, there occurs a seepage of river waters into the banks, that is ground waters are fed by the river. Stationary observations should estimate the magnitude of this phenomenon and determine the width of the zone subject to infiltration of river waters.

Of prime importance in defining the nature and degree of high flood penetration into ground waters is to note the changes of their chemical composition. In doing this consideration must be taken of the amount of water-soluble salts contained in the rock lying above the lower level of the ground water table, i. e., within the zone in which the water table fluctuates under the influence of high flood.

As already indicated, a feature of the watershed type of unconfined (phreatic) water regimes is its formation under the predominant influence of meteorological factors

acting on ground waters through the zone of aeration. Of great consequence to the regime is the thickness of the zone of aeration determined by the depth at which ground waters occur. Accordingly, free ground waters may be divided into two groups:

1. Those occurring at shallow depths and with the zone of aeration of insignificant, or no, thickness. Very important for this group are episodic, and frequently very rapid, changes of individual elements of the regime of ground waters, notably in discharge, temperature and sometimes in chemical composition.

2. Those lying at great depths (not less than several metres) and having a thick zone of aeration. Their regime is distinguished by seasonable variations of the same individual elements.

The processes taking place in the zone of aeration (seepage, condensation, vegetation transpiration) determine the ratio between the water fed to the surface of the water-bearing formation and its discharge, i. e., the character of fluctuations of the ground water table.

Annual changes in the ground water table beyond the zone of river influence and under natural conditions (not disturbed by the activities of man) are in most instances negligible (less than one metre) and rarely reach 1.5-2 metres (when the water table is in the immediate vicinity of the surface of the ground).

When analyzing fluctuations of the ground water table, their varied origin should be taken into account. Some are associated with alterations in the amount of water available in the water-bearing stratum under investigation. These fluctuations are known as actual. Other fluctuations, observed in boreholes, are subject to variations of atmospheric pressure and air pressure within the zone of aeration, when the flow of ground water neither receives nor discharges any water. Such fluctuations were designated by N. N. Bindeman in 1938 as "apparent" and include the following types:

a) those associated with variations of air pressure within the zone of aeration under the influence of water percolating from above or affected by temperature changes prevailing in the zone of aeration (commonly observed during

periods of spring ground thaw and intensive infiltration when the ground water table does not lie deep beneath the ground);

b) those connected with variations in atmospheric pressure (observed when the water-bearing formation is overlain by stratum of low permeability);

c) those connected with transition of water from the capillary to the gravity stage.

In the instance of a very limited zone of aeration, the capillary fringe influenced by rainfall may sometimes reach the ground surface, in which case sharp vacillations of level are observed in wells, their range tens of times exceeding the height of precipitation. This finds its explanation in the pressure of the capillary surface, when it changes its concave shape to that of the flat. Then negative capillary pressure is removed and the layer of capillary water augments, by its weight, the hydrostatic pressure to a height roughly approximating that of the capillary zone. Serious attention should therefore be paid to the study of the height of capillary rise under various conditions of free ground waters.

Apparent fluctuations are exposed by automatic recordings during observations or with the aid of the Simonov level gauge (in instances of frequent gaugings in the course of the day). These fluctuations may be extremely sharp at the time of spring thawing of the frozen soil and underlying ground, when the temperature of these latter rises.

Apparent fluctuations superimpose themselves over the true ones, resulting at times in a rather complex picture of variations in the behaviour of ground water levels. For these reasons modifications in level should be watched during stationary observations.

True fluctuations in the level of the ground water table depend mainly upon precipitation and evaporation. Therefore, when studying the regime of free ground waters the climatic zone of the given regions should always be borne in mind.

Sometimes regimes of ground water, given equal climatic conditions, vary widely due to geological, hydrogeological and geomorphological peculiarities, as well as the

nature of soil and vegetative cover and the thickness of aeration zone at the given site. It should also be remembered that, other conditions being equal, an increase in the thickness of the zone of aeration quite frequently brings with it a time-lag between fluctuations of the ground water table and variations of climatic factors.

The aforementioned considerations underscore the necessity of disclosing and thoroughly investigating all prerequisites influencing the regime of ground waters, so as to obtain complete and comprehensive information. Of decisive importance in achieving this are detailed studies of the region under investigation and a correct placing of observation sites in the network of the given territory.

This observation system should embrace all natural conditions bearing upon the formation of the regime of unconfined waters. The network should therefore be plotted to cover all areas outstanding in climatic features, macro- and microrelief, degree of afforestation, soil cover, depth of ground waters, lithological composition of aeration zone and aquifer, and conditions of ground water drainage. Simultaneously, investigation should include all springs, rivers, lakes, marshes, water intakes, hydraulic works and irrigation systems situated on the territory being covered.

Observation points should be distributed along definite profiles in the direction of ground water flow. This is achieved by the preliminary sinking of groups ("triangles") of boreholes. Furthermore, when specific conditions of the given region cannot be taken account of by the given profiles, a certain number of observation points should be arranged outside the basic profiles.

In a riverside zone, observation boreholes should be distributed along a transverse line so as to include all characteristic elements of the relief—flood plains, terraces and the bedrock bank. Transverse sections should cross the entire area of the river divide.

As a rule, the distance between observation points along the transverse line should increase with the distance from the river (or water basin) towards the watershed in approximately the following sequence: 25, 50, 100, 200, 300 me-

tres and so forth. This spacing is lengthened or lessened according to the thickness and depth of the aquifer, lithological composition of rocks, features peculiar to the relief, vegetation, zone of aeration, etc.

Filters of observation boreholes in water-bearing series should be placed so as to fix the lowest position of the water table. In vertically heterogeneous water-bearing series, groups of boreholes with filters located at different depths should be provided.

The equipment of observation points in the flood plain should include proper protection of observation wells to prevent penetration of flood waters into water-bearing formations both over the edges of the pipes and around the casing. A reserve supply of branch pipes should be kept at the station's warehouse for tightening connections with the base pipe and sealing of joints against possible penetration of high-flood water. During high waters the flooding date of each observation point should be accurately registered; this is quite important for establishing the interrelation between surface and underground waters.

Observation posts should be arranged for carrying out comprehensive observations (levels, temperature, chemical composition). When sharp fluctuations of level occur within the zone of fluctuations of the ground water table, the content of water-soluble salts in the rock should be noted.

When studying the regime of ground waters related hydraulically with rivers and lakes, the regime of surface waters should be taken account of. For this the establishment of hydrometric posts at rivers and lakes is absolutely necessary.

C) THE STUDY OF THE REGIME OF FREE GROUND WATERS OF PIEDMONT TRAINS, INTERMONTANE VALLEYS AND LOW BASINS (DEPRESSIONS)

In piedmont regions as well as in intermontane valleys and low basins a typical group of sand-pebble and clay-sand alluvial-proluvial rock formations are quite frequent-

ly encountered with a specific distribution of ground waters (including free ground water).

In piedmont regions the relief of these formations is evidenced by alluvial cones. They are formed by products of decomposition of mountain ridges transported to piedmont regions by surface waters. These cones are either isolated or, when tied to each other, form piedmont trains widely prevalent in Central Asia and Transcaucasia.

In the submountain regions of Central Asia alluvial cones are usually composed of thick strata of highly impermeable loose clastic rock, very suitable for the storage of considerable reserves of ground water.

Recharge of these waters is effected through infiltration of atmospheric precipitates falling within the range of these cones, through river water and intermittent streams entering the piedmont via the sides of mountain ridges, as well as through drainage via alluvial cones of underground waters accumulated in adjoining mountain ridges.

Ground water thus formed in the valley train flows either in the direction of the piedmont plains (as from the submountain regions of Kopet-Dag to the north and northeast) or towards central parts of intermontane valleys and low basins, the piedmont and valley trains constituting in this case an integral part of the latter (Kura-Araks Lowlands and the basins of Ferghana, Samarkand, Kitab-Shakhrizab, etc.). Towards the periphery of alluvial cones and piedmont trains the coarse clastic material gradually changes into fine-grained aggregate and then into sandy and loess loams. At the edges of the alluvial cones a transition zone is formed, consisting of alternating sand-pebble and loam deposits.

Free ground waters are commonly found at a depth of 60-90 metres in the upper reaches of alluvial cones. Their pitch is much less than that of the surface of the cones. Towards their periphery the depth at which unconfined waters occur therefore decreases, while a partial discharge of free ground waters, forming springs, becomes apparent in the transition zone mentioned above (Fig. 13). In the same transition zone, below the belt of water discharge, confined waters are very often formed in the out-pinching sand-pebble beds.

With the movement of ground waters towards the outer sections of alluvial cones and valley trains, the chemical composition of the flow in most cases undergoes a certain evolution. In the upper reaches of the alluvial cones the mineralization is low with a total hardness of 6-10°. The general mineralization of such phreatic sources gradually increases. Within the belt of the water discharge the hardness reaches 20-40°, while at a still greater distance (in the loess plain) the water becomes saliniferous, saline, and even turns to brine, unpalatable and unsuitable for irrigation purposes.

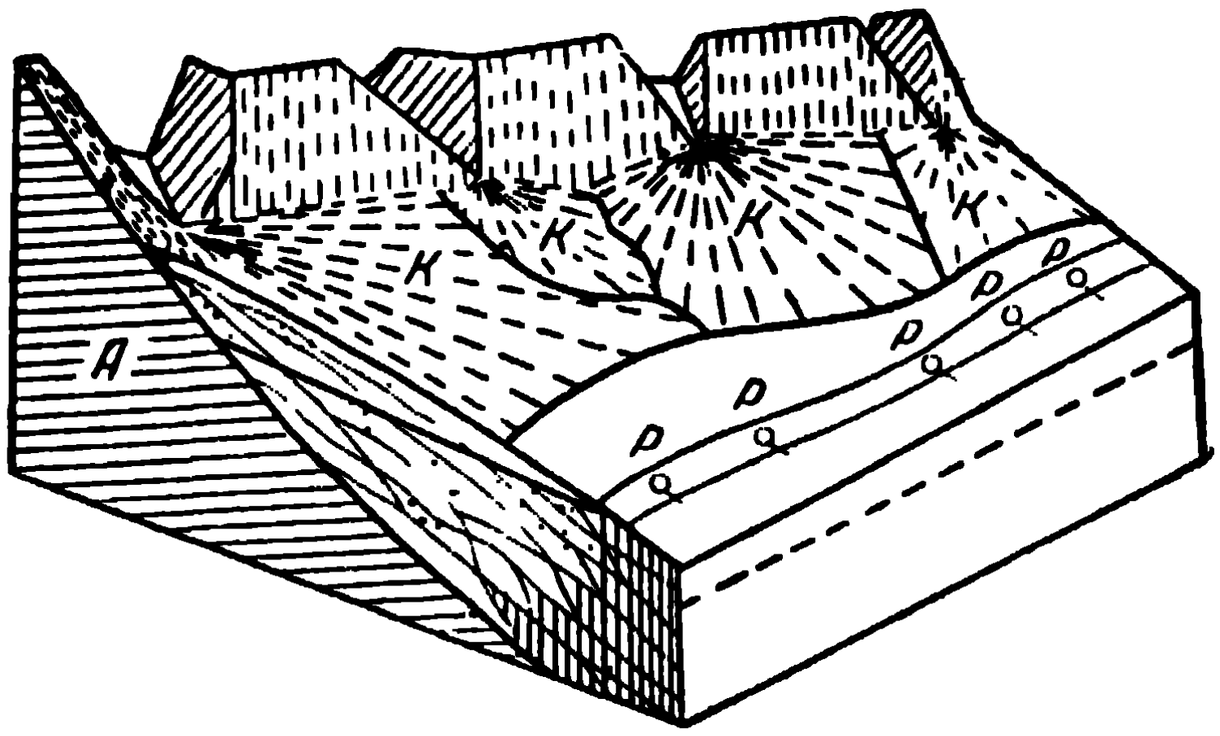

Fig. 13. Schematic view of the distribution of free ground water in piedmont trains (according to O. K. Lange).

A—impervious rock; *K*—alluvial cones; *P*—springs.

This regularity is at times interrupted: individual tongues of rock possessing high water conductivity reach axial regions of adjacent basins; or fine-grained sand-clay material of the alluvial cones in these portions of the basins is washed away and substituted by a coarser material of ancient rivers formerly flowing along the basins. In such cases the axial regions of the basins may also contain confined waters with a low degree of mineralization and subterranean run-off.

Apart from the general circumstances listed above and influencing the regime of free ground water, when investigating such occurrences in piedmont trains, intermontane valleys and basins, due consideration should be given to the distinct zonation of natural conditions away from the mountain ridges towards neighbouring depression areas. Thus in Central Asia the zoning of meteorological factors consists of a gradual decrease of atmospheric precipitates, reaching a point when in the central parts of the depression area the evaporation losses exceed the amount of precip-

itation. A very distinct zoning is observed with regard to soil and vegetative covers. In the same manner the water permeability of the strata almost always declines.

It should be kept in mind that some natural factors participating in the formation of the regime of free ground waters very often are themselves subject to changes caused by man, particularly in construction of irrigation systems and afforestation of large areas.

It is the job of permanent observation stations to distribute their posts so as to permit an adequate study of the influence of all these factors. The first posts should be placed along the most typical lines, starting from submountains (regions of alimentation) towards central parts of the depression area where vertical release of water into the atmosphere occurs through evaporation or transpiration, or where drainage of free ground waters is effected by surface flow. The second group of observation lines should pass along piedmont trains and depressions, so that observation points traversing the alluvial cones are located both in the latter and in the space between. Apart from a detailed study of basic ground water regimes, investigations should also disclose all changes in these factors and, consequently, alterations in the regime of free ground water.

D) SINGULAR POINTS IN THE REGIME OF FREE GROUND WATERS IN SEMI-DESERTS, DESERTS AND COASTAL AREAS

The wide arid territories of the southeastern part of the U.S.S.R. have an extensive prevalence of sand formations, chiefly attended by highly mineralized free ground waters.

In some localities of the semi-desert and desert areas of Central Asia these highly mineralized subterranean waters are superimposed by lenses containing water of a lower degree of mineralization, frequently suitable for drinking. Though the supply of these waters is usually insignificant, they acquire national economic importance due to the shortage of fresh water and therefore deserve attentive study.

A similar situation often exists in sand-covered coastal areas and on sandy islands in the sea. But here such low-mineralized water lenses (such as are found along the coast-lines of the Black and Azov seas, on the eastern coast of the Caspian, and on the coasts of other seas) gain economic importance only in individual districts devoid of surface and underground waters of a better quality.

The formation and regime of waters with a low degree of mineralization and apparently floating on the surface of highly mineralized waters, have not yet been sufficiently investigated. It is assumed that atmospheric precipitates received by sand formations percolate through the latter to the highly mineralized aqueous layer. But the admixture of soft water, with a low degree of mineralization, and the highly mineralized underlayer with its large specific weight, proceeds at a low pace within the sand pores. The result is that the fresh water "saddles" the highly mineralized product, whose surface gradually sags from the weight of the former and the fresh water remains afloat just as in the case of ice.

Together with atmospheric precipitates the recharge may also be effected with pronounced participation of condensation water, particularly under conditions of sharp continental climate. Furthermore, the formation of fresh water lenses in Central Asia is sometimes due to active percolation into the sand of irrigation waters with a low degree of mineralization.

Very often when such waters are drawn from the wells in great quantities, accompanied by an appreciable drawdown of level, an "intake" of saline waters occurs and the wells become useless.

Underground waters in sand-formations of the semi-deserts and deserts of Central Asia (Kara-Kum, Kyzyl-Kum, Muyun-Kum) are formed by infiltrating from the rivers traversing these regions (Amu-Darya, Syr-Darya and others), by run-off of surface and underground waters originating in the mountain regions (Kopet-Dag and others), by the infiltration of atmospheric precipitates, and by condensation of atmospheric moisture.

In 1949 V. N. Kunin pointed out that free ground waters of the Kara-Kum are fed by river filtration (about 74%),

by run-off from the mountain regions of Kopet-Dag (about 11%), and by local infiltration of atmospheric precipitates through the bare sands (about 15%). With an increase of distance from the areas of supply and a lessening of the depth in which ground waters occur, the degree of their mineralization rises, during which process their hydrocarbonate content is replaced by sulphate and then by highly mineralized chloride.

In 1950 Kunin's hypothesis was disputed by E. N. Blagoveshchensky, who, as far as the Kara-Kum is concerned, does not recognize the existence of a continuous unconfined flow, and still less the possibility of its being fed by the waters of the river Amu-Darya. The condensation of atmospheric moisture within the zone of aeration and the evaporation of free ground waters is, according to Blagoveshchensky, of outstanding significance for the regime of unconfined waters. The relation between these factors, in his opinion, determines the balance of ground waters and their quality: "Other conditions being equal, the total liquid recharge-discharge balance of the water table is determined by the depth of its occurrence. In the region of Kara-Kum the critical depth where condensation is overtaken by evaporation comprises 5-6 metres. Therefore, it is only in extreme cases that fresh water is encountered at this depth. Usually if the depth of the water table is less than four metres, the water is saline even in completely bare barkhan sands. At a greater depth, where a sandy eolian cover is encountered on the surface of denser ancient alluvial sediments, the water as a rule is fresh even in regions where thick formations of upper Tertiary sandstones lie above the water table."

When studying the regime of free ground waters, due consideration should be given to all these diverse viewpoints.

In accordance with the suggestions made by Kunin, observation cross-sections should be spaced along ground water flow so as to include all the regions of recharge, transit and evaporation loss into the atmosphere. Blagoveshchensky contends that a thorough investigation must be made of all moisture dynamics within the zone of aeration.

The most interesting subject for practical purposes in

the regions under consideration is that of fresh ground waters occurring as lenses lying on highly mineralized water. When studying its regime the network of observation points should be arranged along alignments perpendicular to each other and should terminate outside the boundaries of such fresh water lenses. Particular note should be taken of the duration of changes in chemical composition along vertical paths, both under natural conditions (undisturbed by man's activities) and under the influence of test pumping at different levels of the water table, the object being to determine the optimum draw-down level that causes no "suction" of underlying highly mineralized waters.

E) THE STUDY OF THE REGIME OF FREE GROUND WATER UTILIZED FOR WATER SUPPLY

So far our investigations have dealt with ground waters in their natural states (undisturbed by the activities of man).

Free ground waters affected by existing or future structures which will influence the regime of such sources will be discussed in the following sections of the present chapter. Here our study of the subject will only touch upon water supply, it not being treated elsewhere.

The network of hydrogeological observation posts situated in regions of intended large-scale water intakes must be supplemented by new points which, together with those already existing, should provide a minimum of two perpendicular observation alignments passing across the site of the planned water intake. One of these lines should run parallel with the movement of ground waters, the other—perpendicular to it.

To properly coordinate the data relative to the regime of free ground waters both in their natural state as well as in the area disturbed by water intakes, the terminal observation points of the alignments should be sunk outside the zone of depression cones, the formation of which might be possible during the operation of the said water intakes.

Investigations at supplementary points are to be started

prior to commencement of intended construction, after the completion of which systematic observations are to begin of catchment yields, dynamic levels, temperature, and of bacterio-chemical (and sometimes gas) composition of the water. Particular note is to be made of development of local and regional depression cones influencing the yields of water intakes, as well as variations in the chemical composition and temperature of the water resulting from the operation of the given undertaking. The purpose of these observations is to prevent any possible depletion of supply or deterioration in quality of the phreatic sources due to any changes in the rate, or area increase, of water extraction.

Any changes in, or deterioration of, the quality of water may be due to "intake" of river, sea or marshy waters, of industrial or other poluted waste, or "intake" possessing a higher degree of mineralization originating in other aquifers; or the cause may be related to physical and chemical processes in the zone of water table fluctuation within the limits of depression cones.

Thus, when water was first pumped at a certain completed structure, it held approximately six milligrams per litre of iron; no manganese compounds were detected. The quality of the water was found to be good.

During the first year of operation (water extraction) the iron content gradually increased to 20 milligrams per litre; after the wells were flooded by high water it rose at individual wells to 80-100 and 400 milligrams per litre. Moreover, manganese detected in some of the wells amounted to 200 milligrams per litre, after which the water was considered unsuitable for domestic supply.

These iron and manganese enrichments of free ground waters found the following explanation: water-bearing alluvial deposits were overlain by silt formations containing sulphurous iron and up to 20% manganese oxide. During pumping, silt formations were drained with subsequent intensification of oxidation processes, resulting in the transformation of non-soluble salts of iron and manganese into soluble. Atmospheric precipitates and high waters filtering through these silt formations transported the salts down to the aquifer.

Table 6 may serve as another example of changes in the quality of water in the course of its extraction during the 1805-1910 period (when so-called super-jurassic aquifers were involved):

Table 6

Year	Dry residue mg/l.	Total hardness German deg.	SO_4'' mg/l.	Cl' mg/l.	Fe_2O_3 mg/l.
1805	145	6.25	4.8-8.4	2.5	0.31
1910	501.7	21.7	139.56	5.1	1.31

Causes for the changes in quality of the water were based on increased extraction from the aquifer, accompanied by the lowering of the water table and a higher water mineralization due to transition of non-soluble compounds, largely those of iron, into soluble solutions. This phenomenon was the result of oxidation processes, the intensity of which greatly increased in the drained zone within the limits of the depression cone and particularly in the areas covered by peat bogs.

Timely prevention of possible changes in the quality of water in wells and the recommendation of a rational rate of extraction would necessitate ascertaining which of the areas on the territory under investigation may become the source of such changes or deterioration in quality during pumping.

A number of observation points distributed along alignments starting from such areas and directed towards intended or existing wells should be sunk for the study of the ground water regime, with particular emphasis given to chemical changes, and sometimes to the gas composition of the water.

2. THE STUDY OF THE REGIME OF ARTESIAN WATERS

Artesian basins represent a system of water-bearing strata hydraulically related in one way or another to each other and occurring in negative geological structures of the earth's crust.

There are extremely diverse types of artesian basins, varying in area and number of water-bearing strata and depth from the ground. Of the greatest importance for the national economy are those of the Russian tableland, such as the Moscow, Dnieper-Donets and Black Sea coast basins, all very large and comprising several aquifers with an abundance of potable water.

Methods of investigation of the regime of artesian waters are dependent upon geological conditions, basin area, and number of aquifers and their interrelation.

Artesian waters are chiefly utilized for water supply and irrigation. Furthermore, they serve the purposes of balneology and are mineral sources for the chemical industry.

Studies of artesian resources and their balance, aimed at rational planning for future supply, presents a question of national economic importance.

This task involves collecting and coordinating of all data on geology, hydrogeology, climate, hydrology and extraction methods of artesian waters. For this, studies must be made of: a) conditions relative to recharge, movement and drainage of artesian waters; b) temperature, chemical composition (including microconstituents and radioactivity) and bacterial population; c) water-conducting properties of aquifers and velocity of underground flow; d) water yield of boreholes (specific yields), draw-down, radii of influence of independent wells, depression cones, sum of pumped water and, lastly, techniques of artesian extraction with emphasis on arrangement of borehole filters.

Although the range of artesian level fluctuations affected by natural factors is usually insignificant, it should nevertheless be determined for each region for calculating artesian operation levels.

Forecasting changes in artesian level is important not only for water supply, but also for extraction of coal, crude oil, gas (and other minerals), as well as mineral waters for medicinal purposes. In a word, such forecasting should be based not only on information relative to natural regimes, but also on data obtained as a result of extraction in regions of mineral deposits and mineral waters, i.e., the problem should be handled in an all-embracing manner.

The immediate tasks in the study of artesian waters are those of anticipating their resources, foretelling the development of regionl depression cones and, finally, the solution to the problem of individual aquifer depletion.

Control of the regime of artesian waters should chiefly mean: 1) rational siting of artesian wells ensuring a maximum of pumped water with a minimum expenditure, and 2) adjustment of operating level with the object of maintaining fixed relations between water levels in operating wells on the one hand, and levels of highly mineralized waters (or sea-waters) on the other, which in some measure makes it possible to eliminate the penetration of waters with a medium or a high degree of mineralization into extraction areas. In some cases this may also involve the problem of artificial recharge of artesian waters.

Solution of all the above items calls for an inquiry into all aquifers in the given artesian basin, also of free ground waters in some regions. Observation wells should be sunk throughout the area covered by each aquifer and in numbers sufficient to compile fairly accurate piezometric surface maps of the aquifer for any given period. Investigations should simultaneously embrace the network of operating wells.

The study of the regime at isolated points is of small practical and scientific value. Each hydrogeological station engaged in investigating artesian waters should be provided with a thoroughly prepared schedule of observation point distribution. The realization of such a plan should proceed gradually over a number of years in full conformity with national economy development within the given district.

The growth of a widespread observation system throughout the artesian basin should begin with the selection of principal aquifers of major national economic worth and the sinking of observation wells along one or two basic transverse sections. Extension of such a network is then carried out through a gradual increase in the number of transverse sections.

Observation wells on these transverse lines should describe: a) recharge areas where artesian aquifers occur partly as unconfined waters; b) areas of pressure water movement;

c) drainage areas which may include large rivers, seas or oceans lying adjacent to the artesian basin and, lastly, d) areas with large artesian waters withdrawals. Of course, the position of intake and drainage areas cannot be always established at once, for which reason the distribution of observation wells should be gradually corrected according to the results of detailed research.

Intake areas of artesian waters may have a variety of geological and hydrogeological prerequisites. Hence, basic transverse sections passing across the whole of the artesian basin should be started from one test plot, or, if possible, from several such plots, on which investigations of basic types of artesian water recharge are being conducted.

The study of the recharge of artesian waters should be carried out by establishing a number of small transverse sections distributed in conformity with local geological and hydrogeological structure.

Of extreme importance for test plots situated in the areas of recharge is an inventory of individual aquifers and their relationship. Hence, well filters should be placed in as many water-bearing beds as feasible.

In addition to special observation bores established for inquiry into factors of recharge, the test plots should embrace available springs and other points where the regime of surface waters is being learned.

A number of boreholes should be sunk for routine observation cycles, beginning from each test plot and running along the transverse section approximately across the strike or the axis of the artesian basin. The purpose of such an investigation is to learn the regime of artesian waters in the area of pressure movement. As a rule, new holes are drilled or selected from among existing ones not under operation but whose logs are known. Flowing wells or those operating only during certain seasons of the year (for example, for irrigation during the vegetation period), and those used to observe the development of the local depression cone, form an exception to the rule.

Basic transverse sections for many artesian basins (the Moscow, Dnieper-Donets, and other artesian basins) should include those cutting across areas with intensive artesian extraction. Typical of such areas are large cities (such as

Moscow, Kiev, Kharkov) and large industrial enterprises. These districts should be covered by a network of observation bores permitting the investigation of the dynamics of water withdrawal and to follow the development of any local depression cone. This is needed to determine underground water resources and their possible depletion.

Such a system of observation points in areas of intensive withdrawal should include both unutilized and utilized wells; the first enable us to more accurately follow general variations in water level, while the second establish the relation between yield and draw-down at individual points and better ensure noting of water temperatures and collection of samples. Unused wells, if possible, should be uniformly chosen throughout the territory under examination. They should be located both in the vicinity of pumping centres and at some distance away, and should include some outside the sphere of influence of pumping operations. Furthermore, it is usually found that additional ones must be drilled.

In most instances a more or less accurate location of natural drainage areas for deep-lying artesian waters is unknown. Natural drainage of certain small artesian basins is sometimes effected through outlets to the ground or by means of artesian springs. In such cases observations should include all springs, or ground seepage.

The usual full sequence of observations should be undertaken in all wells intended for the study of the regime of artesian waters.

We will now examine some aspects of the work of hydrogeological stations engaged in the study of artesian regimes.

Geological and hydrogeological research of artesian basins must be conducted both by the study of available literature (including files) and by means of supplementary field investigations of recharge and drainage areas. The scope of the work should contain all possible studies and field surveys, particular consideration being given to the collection of information concerning drilling of new artesian wells.

The compilation of piezometric surface maps for typical periods of the year is of first consequence, for the achieve-

ment of which the hydrogeological station should possess an annual plan of operation of single water level gaugings in all observation holes, both throughout the territory as a whole and in individual areas of intensive exploitation of artesian waters. To prepare maps of water yields for individual aquifers, the systematic collection and coordination of data relative to artesian exploitation, both trial and actual, is necessary. Approximate yield maps may be compiled according to volume yields of the wells; maps of a higher accuracy may be drawn up from data of specific (unit) yields. More accurate maps may be obtained if the constants of specific yields are based upon equal draw-downs for all borings and then the map plotted with water-yield coefficients, representing a unit yield with an equal draw-down, divided by the tapped thickness of the aquifer. It should be noted that the value of these coefficients is dependent in large measure on the diameter of the filter or the final diameter of the boring. Therefore, if possible, borings of equal diameter should be taken when computing these values, in order to arrive at comparable figures.

Apart from maps showing water yield, those of water permeability should also be compiled. This can be done if the information on hand enables the computation of coefficients of filtration for individual points, with consideration given to the heterogeneous nature of water-bearing strata along their vertical cross-sections. In the absence of such data, the radii of influence and the degree of interaction of the borings are ascertained by tests.

Particular attention should be allotted to the chemical and gas composition of artesian waters and to the compilation of hydrochemical maps. The latter are based on chemical analyses and may differ considerably in content, depicting variations in the degree of mineralization (dry residue), individual chemical elements and gases, types of water and so on.

Examination of artesian waters with reference to content of rare elements, gases and microflora acquires no small importance.

Our concluding remarks concern the study of the regime of oil-field waters, which in their hydrogeological nature may also be referred to as artesian.

Oil deposits occur at depths of 500-1,500 metres, in the midst of highly mineralized artesian waters. In their relation to the whole artesian basin, oil deposits represent small pools where the pressure head of artesian water declines over a prolonged period as a result of oil (gas) extraction and, in watered oil wells, of water extraction. Oil-field waters are classified as follows: a) top waters occurring in water-bearing formations lying above the oil deposit; b) lower waters lying below the oil deposit; c) bottom waters whose lower extremities are in immediate contact with the oil deposit and confined in the same water-bearing formation as the oil; d) contour waters found in the zone surrounding the oil deposit.

A number of cases may be cited when, due to a drop of pressure head in oil deposit areas during pumping of oil and gas (and partly of water), the bottom and contour waters were drawn "tongue-like" towards the oil layer, resulting in increased watering of the oil deposit. Technical deficiencies of boring and at times tectonic disturbances will subject the oil deposit to watering by the upper and lower divisions.

In 1951 A. I. Silin-Bekchurin gave the following general description of oil deposit flooding:

"Following a depression of strata pressure during exploitation of a deposit, a hydrogeological change sets in and an inflow of oil begins towards the area. Since the viscosity of water is considerably below that of the oil, the velocity of its movement along the stratum exceeds the velocity of the oil. Water overtakes the oil and, reaching the wells sooner than the oil, begins flooding them. Firstly cones of bottom waters are formed. Then contraction of the petroliferous contour begins. Because of the difference in permeability of the rock this phenomenon is not uniform. Tongues of contour waters begin forming which penetrate the oil-field along the course of greatest permeability. When approaching the wells where the pressure is down, the contour waters are transformed into bottom waters and rise, forming flood cones."

All this results in a sharp worsening of operation in the oil-field and makes the task of combating oil flooding a question of paramount importance. The proper solution

of these problems requires systematic stationary observations of underground water in the regions of oil-fields by special hydrogeological stations.

The principal job of such stations should be the study of the regime of underground waters in oil regions with the aim of rationally siting oil wells and working out measures against flooding. Such stations should study: a) the geology and hydrogeology of oil-fields on broad regional principles; b) changes in head pressures, temperature, and chemical and gas composition of waters in aquifers which might be responsible for watering; c) the degree of oil deposit watering, its sources, direction and extension of flood cones formed by bottom waters, and the course followed by contour waters in their movement towards oil deposits. Stations should collect data relative to oil-well design and rate and quantity of water and oil extraction, and also investigate the efficacy of measures against watering of oil-fields on the basis of operating data.

Following such observation, forecasts of the movement of contour waters and flood cones in the deposit are to be compiled. Information on the efficacy of measures adopted against watering together with warnings of such an event will serve as a basis for combating oil-field flooding.

Observation borings intended for investigating artesian water regimes in oil regions may be distributed in a variety of ways, subordinated, in the main, to the geology and hydrogeology of the given oil deposit and to the proximity of artesian recharge areas.

Should the areas of recharge be near an oil producing region (as in the Grozny district, Daghestan), the general scheme for the distribution of observation points will remain in principle the same as commonly accepted for artesian basins: the observation system will be composed of individual posts distributed in artesian recharge areas, artesian movement areas and, lastly, in the district of oil, gas and water extraction. Such posts should be also placed along transverse sections running from the area of recharge to those of intensive extraction.

If the areas of recharge are sufficiently distant from an oil producing region (as for example in the Volga-Ural province), it will suffice to locate observation points directly

in the latter and thus include contour, bottom, and sometimes upper and lower waters.

The distribution of observation wells in an oil producing region largely depends upon geological conditions under which the oil deposit occurs. A full study of artesian waters may be effected by sinking boreholes along two perpendicular transverse sections. In deposits of irregular shape other systems for the distribution of observation wells may be applied, with due thought to the geological structure of the region. The total network of observation posts should include the greatest possible number of operating bores.

Due to large costs of sinking observation holes in oil-field regions, prospect borings should be made use of, not forgetting to provide for this in advance in corresponding plans of geological and prospecting work.

Apart from the series of routine observations, hydrogeological stations studying the regimes of oil-field or artesian waters should also investigate the geology and hydrogeology of the region and compile charts of piezometric surfaces, water permeability, hydrochemical and gas composition, draw maps of flooded areas, etc.

3. THE STUDY OF THE REGIME OF UNDERGROUND WATERS IN PERMAFROST AREAS

The regime of underground waters in regions of permafrost differs appreciably from conditions elsewhere.

Some types of underground flow periodically or sporadically change their state from liquid to solid, from unconfined to confined, or acquire a higher degree of mineralization. Conditions of recharge, flow and aquifer interrelation are likewise liable to alteration.

Variations in discharge, temperature, chemical composition and physical properties of aquifers should be studied jointly with conditions of freezing and thawing of the ground.

The study of the regime of underground waters should be accompanied by an inquiry into the trend of frost action, i.e., the degree to which permafrost grows or lessens in relation to the underground water regime.

Where the permeability of rock outside the permafrost region is relatively constant in time, in regions of eternal frost all frozen rock is water-tight (provided the subterranean water is not briny), but after thawing, or even at a raised temperature, it becomes water-permeable.

In investigating the subject, artificial factors should be considered in detail, since almost any engineering undertaking will affect the temperature of the frozen ground and subsequently influence its hydrogeological status.

Particularly big changes in underground waters occur with the construction of water storage facilities capable of thawing permafrozen ground, entirely altering its filtration properties and strongly influencing the conditions governing recharge and drainage of aquifers.

Construction work over large areas greatly affects the upper horizons of underground waters.

Systematic and prolonged mine pumping which warms the surrounding terrain affects the regime of underground waters, particularly causing their flow into the mine workings.

Large fills and dumps of mullock at open pit mines very often qualify the forming of permafrost; this naturally also violates the regime of underground waters.

The hydrogeological station investigating underground water regimes should cover a definite physico-geographical zone and a precisely delineated region of permafrost.

The plot for stationary observations should be chosen following special explorations of permafrost conditions, the methods for which are set forth in detail in corresponding manuals compiled by M. I. Sumgin in 1933, V. K. Yanovsky in 1936 and I. Y. Baranov in 1938.

Such inquiries are to be carried out in two stages (a general survey and a detailed study) and are to be conducted during correspondingly different seasons of the year.

The general survey renders good results when done at the close of the winter, when hydro-permafrost phenomena are at their height and seasonal freezing is at its minimum. The lowest temperature of the active layer may be found at this time, as well as seepages of permanent springs and their approximate discharge (according to basins created upon the ice), the minimum capacity of water-bearing

strata and the contour lines of taliks. All this information will enable a more precise choice to be made for the station site, at the same time minimizing the amount of costly and elaborate investigations.

The detailed study is conducted twice a year—in the interval between summer and autumn, and in the spring.

Autumn investigations are best for: completely revealing the typical relief of permafrost meso- and micro-forms (thermal karst, solifluction, spots of medallion pattern, stone polygons, etc.); establishing the depth of seasonal thawing; registering indications of water-holding qualities during the period of the most intensive underground water recharge; determining the depth of ever-frozen ground.

Repetition of the investigation in the spring permits the establishment of maximum winter freezing depth, the disclosure of non-freezing taliks, permanently active springs and their temperature and chemical composition.

The most rational method for the choice of stationary observation sites during the general survey is that of cross-routes, while areal surveying is best during detailed study. Charts of permafrost conditions compiled for the general survey should be made at scales of 1:50,000-1:100,000, while those for subsequent detailed work—at scales of 1:10,000-1:5,000 and larger. For field work a topographic basis 2-3 times larger than the scale of the given survey is required.

Investigations preceding the stationary observations should clarify geological structure, the state of underground water recharge, links of aquifers, and the way in which the discharge of underground waters to the surface of the ground is effected.

On the basis of this data an observation area is determined and distribution of observation points within the given area effected.

The work of the hydrogeological station should be all-embracing and include, besides the study of the underground water regime, a systematic inquiry into seasonal freezing and thawing of the ground, its temperature and moisture variations, thickness and distribution of the snow cover (especially valuable in the study of water occurring above the permafrost stratum), behaviour of open reservoirs,

and dynamics of changes during the hydrofrost process (upswells, heaving of the ground, building up of ice caps, etc.).

All types of underground waters should be looked into (below permafrozen level, in between its layers and above it).

Waters occurring below the ever-frozen level are tapped by borings. Usually one or two boreholes are sufficient for the purpose (depending either upon the number of water-bearing strata found below the level of the eternally frozen ground or upon the purpose of the observations). A single boring for simultaneous investigation of several horizons with the use of the piezometer or by means of several individual pipe columns sunk into the beds under study are not permissible under permafrost conditions. At the same time observations should be made of water sources under the permafrozen ground as well as the ice caps formed by them.

Stationary observations of waters occurring under the permafrost are complicated because the piezometric level ordinarily stands above the lower level of the frozen stratum and the water freezes in the borehole. This may be overcome chiefly by systematically heating the holes with steam or hot water. The use of salt brine is impermissible since it inevitably changes the water density and gives false readings. Electric current is also resorted to for heating the hole.

Flowing wells never freeze even if giving only small yields. The same is true of highly mineralized water.

Observations of waters lying between the layers of permafrozen ground are examined in a similar fashion, with the difference that a greater number of observation points are required than when the water is below the level of the frozen ground.

Pits are used to study the regime of waters occurring above the level of eternal frost, and boreholes employed for deep waters or those under the beds of open reservoirs.

Levels and temperatures should be recorded:

a) once in ten days throughout the year for waters lying beneath ever-frozen ground;

b) once every five days throughout the year for waters occurring between layers of permafrozen ground;

c) once a day for waters lying above the ever-frozen surface, and once every 5-10 days after complete freezing of the stratum.

Yield and chemical composition should be determined twice a year—in the spring and autumn, when water-bearing formations may be expected to occur at their maximum.

In winter, borehole and pit pumping should be conducted with pumping plants installed in heated premises.

In airlift pumping the air lines are often clogged by ice from condensed moisture. To avoid interruptions, several types of heaters and shoes with non-return valves for air-feed pipes have been proposed.

The borehole or pit should be enclosed in an insulated shed. It is also advisable to locate the mouth of the borehole within the pit and cover the latter with a felt-padded lid.

To stop bulging of shed timbering by the frost in cases of prolonged observations, a layer of gravel should be placed on the outside. A clay seal is to be provided to prevent operation interference by the penetration of surface water.

Springs under systematic observation should be provided with an adequate insulated catchment or spillway in the form of a wooden pipe covered with moss and earth.

A bench-mark should be set up at the station for level control.

Due to seasonal freezing and thawing of the ground a geodetic bench-mark of the common type may be subject to vertical and horizontal distortions under conditions of permafrost, necessitating the use of bench-marks of a special design.

The Tsitovich bench-mark consists of a pipe with its diameter somewhat smaller than that of the bored hole. The pipe is lowered into the ground to a depth three times the thickness of the active layer. The lower part of the pipe is perforated. Water is then poured into the hole until it reaches the roof of the eternally frozen ground. The frozen water forms a reliable bond between the pipe and the frozen stratum. For a heat insulator the frozen water is then covered with dry sand and dry peat. A metal rod is then introduced into the remaining free section of the pipe and cement grouting poured in. To assure still greater dependability of the arrangement the head of the bench-mark may be surround-

ed by a hill of dry sand and covered with a thin layer of peat, with sod above it.

The Melnikov bench-mark is either a pipe or a wooden pile installed in the pit and reliably secured to the frozen ground by means of cross-beams.

Bench-marks should be installed during the winter. The pit should be sunk 1.5 metres below the active layer and then packed with wet.soil laid in consecutive bands of 10-20 centimetres, each layer being placed only after the preceding has frozen. Above the zone of eternal frost the pit is filled with dry earth over which a peat or moss pile is thrown to a hoight of 0.8 metre and the pile then sodded.

Bench-marks of the design described above are set up in the absence of a dependable outcropping of rock on which a small flat area may be hewn or the bench-mark secured.

4. THE STUDY OF THE REGIME OF FREE GROUND WATERS IN IRRIGATED AREAS

A) GENERAL AIMS

Irrigation represents a cardinal improvement of lands under cultivation.

Meliorative measures require comprehensive and varied investigations into soil, selection, agrotechniques, etc. Also of first-hand importance are hydrogeological studies of the territory and, particularly, of underground water regimes. The history of irrigation in the regions of Central Asia, Transcaucasia, Transvolga and other areas shows that irrigation systems built without sufficient consideration of local natural hydrogeological factors cause swamping and salination of large land areas, with resultant huge losses to the national economy.

The reconstruction of old irrigation systems and the cultivation of new agricultural areas require a knowledge of the complex processes leading to the formation of saline soils. Such knowledge is needed to direct the processes leading to desalination and improvement of soil fertility. Since free ground waters play a decisive role in soil salination, any conclusions as to possible changes caused by

irrigation as well as measures to be taken against the detrimental effects of supplementary soil humidification may be based only on pertinent data of free ground water regimes.

Methods of study of this subject as offered in this chapter are, in the main, applicable to irrigation regions of Central Asia.

Among our fundamental aims are:

1. To reveal genetic and regional phenomena governing the regime of free ground waters; this will serve as a basis for a reclamation evaluation of the territory as well as for classifying the land in its relation to water supply.

2. To study the influence of canals, irrigation waters and drains on free ground water and estimate any possible changes in hydrogeological conditions in connection with the reconstruction of old irrigation systems and the development of irrigation on new territories.

3. To study the water-salt balance in the territory under irrigation.

4. To determine the effectiveness of collectors and drains on the water-salt balance of free ground water, as well as to appraise the part played by trees in lowering the water table.

5. To forecast the free ground water regime in newly irrigated areas.

6. To determine the possible utilization of underground waters for irrigation and water supply.

7. To determine the possibility of regulating the regime of return waters.

All this demands a thoughtful plotting of the system of observation wells.

When examining the behaviour of free ground waters exclusive attention should be paid to the part played by individual sources in recharge, as well as evaluating the role of various parts of the natural and artificial hydrographic network in drainage. Approximate relations between the dynamics of recharge and the cropping out of ground waters may be disclosed by collecting, systematizing, and properly digesting the data supplied by field hydrometry.

The questions of primary and secondary salinization of

the soil by free ground waters and the choice of measures against these processes—that is, restoration and improvement of the fertility of the soil—constitute one of the cardinal problems of agriculture, particularly in irrigated regions noted for difficulties in the run-off of surface and phreatic waters. This especially involves research into the hydrochemical regime of free ground waters.

Hydrochemical investigations require a parallel study of the water-salt regime of the soil profile, this being essentially a regular soil and agromeliorative theme; investigations should, therefore, combine soil and hydrogeological observations.

Of particular importance when analyzing the regime of ground waters is the establishment of the relationship between water table fluctuations and the dynamics of water delivery.

Of all the elements of balance in free ground waters, special points comprise evaporation and transpiration losses, supply by means of surface filtration and through upward leakage of confined waters. Furthermore, in order to draw up the inventory of free ground waters of the oasis as a whole and along its boundaries with the desert, the influx and outflow of these waters should be established.

An exclusive question is the study of horizontal migration of salts and their individual components, due to free ground water flow intensified by irrigation, as well as of run-off towards the collecting and draining system. Of no less importance is the study of water movement and migration of salts within the capillary zone and observations of water delivery velocity along the capillars towards the desiccation horizon.

B) FEATURES PECULIAR TO THE REGIME OF FREE GROUND WATERS IN IRRIGATED REGIONS

It is well known that intensified supply of free ground waters due to irrigation alters their natural regime.

Despite the fact that the irrigated regions of the U.S.S.R. are located within a belt of comparatively uniform climate, the whole scale of physiogeographical and, particularly, hydrogeological conditions of the irrigated territories is

extremely diverse. No less diversified are the regimes of free ground waters within the limits of one and the same area.

Irrigated territories may be divided into two basic groups, depending on conditions of salt accumulation and the water-salt regime of the soil. The first includes drained areas where, among all the discharge items of the water balance, underflow prevails. The major part of irrigated areas, however, belongs to the second group where underflow is practically nil.

Let us then examine the nature of changes in the regime of free ground waters of both of these groups.

1. Features Peculiar to the Regime of Free Ground Waters in Irrigated Regions with Adequate Underflow

A distinct feature of the regime of free ground waters in these regions is a very narrow range of water table fluctuation. The water-salt balance is characterized by processes of natural desalination.

Irrigation during the vegetation period is marked by a high water table, followed by a prolonged period of its decline.

In those sections of river valleys where, prior to irrigation, phreatic waters were fed by a river, the latter frequently assumes the role of a drain, with seepage of free ground waters and the formation of swampy ground on its lower terraces.

In areas where, prior to irrigation of the valley, unconfined waters were drained by a river, the feeding of the latter by these waters becomes still more intensive. This peculiar phenomenon has been very aptly designated in irrigation practice as "the process of return water formation."

The study of the formation and regime of these waters is of appreciable value both in anticipating their utilization for purposes of irrigation and foreseeing possible deterioration of land adjoining the irrigated block where return waters seep out.

On lands with deep natural drainage, phreatic waters after irrigation have no active link with the soil profile;

in other words, irrigation waters exercise a very mild influence on the behaviour of the water table. But where shallow drainage prevails, surplus irrigation and a rise of the water table lead to excessive soil moisture.

Quite often irrigated areas with natural drainage are considered by the irrigators as possessing an "outflow guarantee" and, consequently, standing in no need of reclamation. Such a conclusion, however, may prove erroneous; an underflow, such as from pebble beds of a valley train,

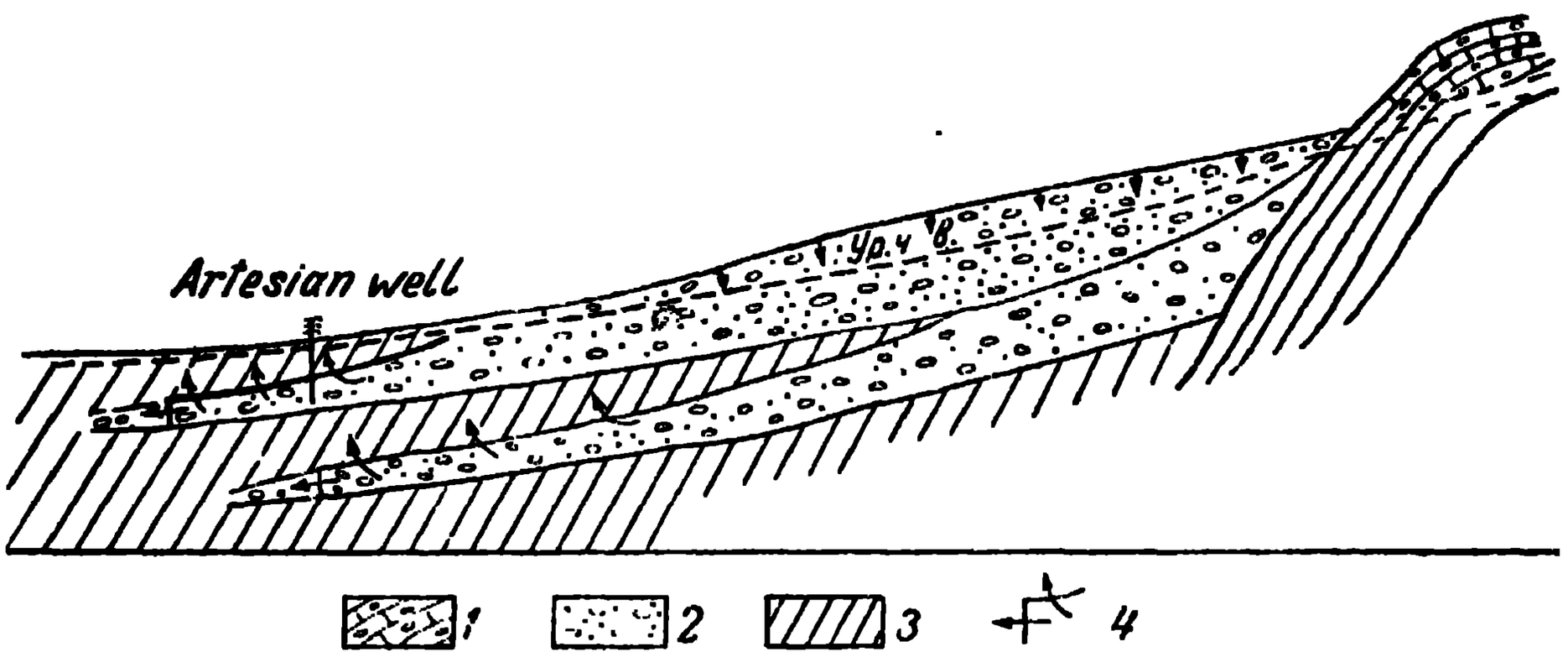

Fig. 14. A contemporary alluvial cone.

1—conglomerates; *2*—pebble beds; *3*—sand and clay deposits; *4*—lines of flow.

is largely dependent on the transmissibility of the entire hydrogeological system. For example, in pebble "tongues" of valley trains occurring at the periphery of the latter, the conditions for water circulation are unfavourable because the pebbles are replaced by sand and clay sediments (Fig. 14).

2. Features Peculiar to the Regime of Free Ground Waters in Irrigated Regions with Inadequate Underflow

The majority of irrigated regions of Central Asia and the Transcaucasus have no adequate underflow.

Distinctive features of the regime of underground waters in these areas are: shallow unconfined waters which, at times, reach a critical depth of 1.5-2 metres; clearly pronounced seasonal fluctuation of the water table; consid-

erable rise in level following irrigation, sometimes marked by a maximum summer level in irrigated areas.

The water-salt balance in these regions is conducive to salinization both of the soil and the phreatic flow, the salinization process resulting in the formation of saline lands and evaporation constituting the predominant item in free ground water decrement.

Fig. 15 illustrates the levels of ground waters in the Golodnaya Steppe before and after irrigation. Before the introduction of such measures the water table lay at a great

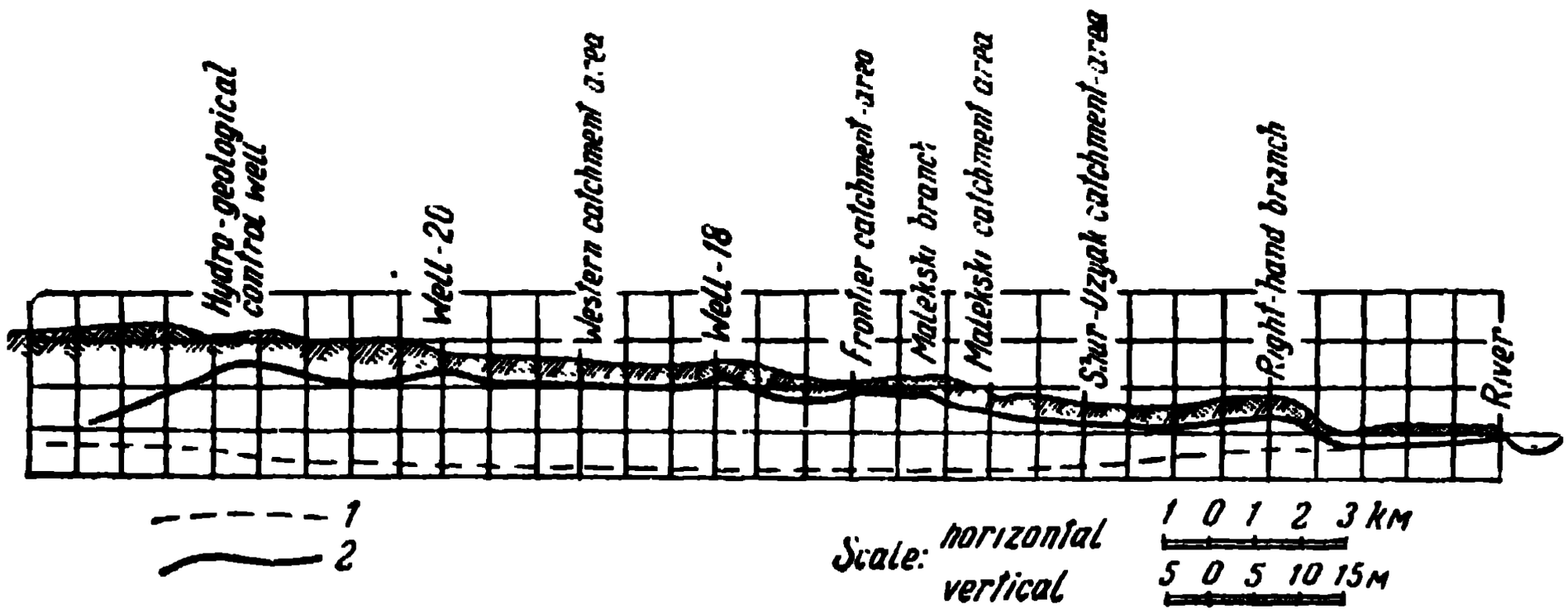

Fig. 15. Effect of irrigation on the free ground water level in the Golodnaya Steppe (according to M. M. Krylov).

1—free ground water level prior to irrigation (1908-1911); *2*—free ground water level in 1934-1935.

depth, but after irrigation it rose noticeably everywhere on the territory and finally stopped not far from the ground, corresponding to the balance between rates of recharge and discharge through evaporation and transpiration. This resulted in intensive processes of secondary salinization of the soil.

As shown by investigation, the distinguishing features of this new regime created by irrigation were:

1. Seasonal phreatic level fluctuations in the irrigated area, largely regulated by evaporation and transpiration (maximum in the spring, minimum in the autumn).

This seasonal unsteadiness, complicated by "irrigation peaks" on irrigated plots, altered completely under the hydrodynamic influence of the irrigation ditches within a 200-300 metre zone adjacent to the latter.

2. Very marked level fluctuations of unconfined waters over a number of years, which are of particular importance because they determine sharp changes in the conditions of land under reclamation. The principal reason for such extended level irregularities is explained by changes in the volume of annual recharge, both from underground inflow and irrigation draft from the river. A correct interpretation of the relations existing between these factors for each individual case may be found not only by means of observations of the regime of the upper layer of free ground waters, but also of deeper flows.

Fig. 16 gives an example of a large rise in phreatic level which occurred during the extension of an irrigated area within the limits of bad lands. It should be noted that the constant rise in the level of unconfined waters year after year was accompanied by the usual seasonal fluctuations. In 1945-1946 irrigation of the new area was discontinued and extensive drainage inaugurated where the rise in level had resulted in destruction of trees and houses and the swamping of the territory. As a result of these measures, the waters subsided. Irrigation under conditions of difficult phreatic underflow leads therefore to the progressive growth of free ground water reserves (due to increased supply and insignificant discharge) and hence to a rise in level. As the water table approaches the surface of the ground, the part played by evaporation and transpiration correspondingly increases.

In a reclamation evaluation of free ground water regimes it is very advisable to apply the method proposed by M. A. Shmidt in 1940—that of the simplest analysis of level fluctuations.

This method consists in charting all factors of the regime on chronological graphs, as shown, for example, in Fig. 17.

The curve illustrating the direction of natural fluctuations in the level of free ground waters is determined on the basis of natural laws governing the regimes of these waters established in accordance with observations conducted in areas where there are no temporary rises in level caused by irrigation. Such areas may be chosen without difficulty on the basis of prolonged investigation. A graph treated in this manner gives a very graphic representation of the in-

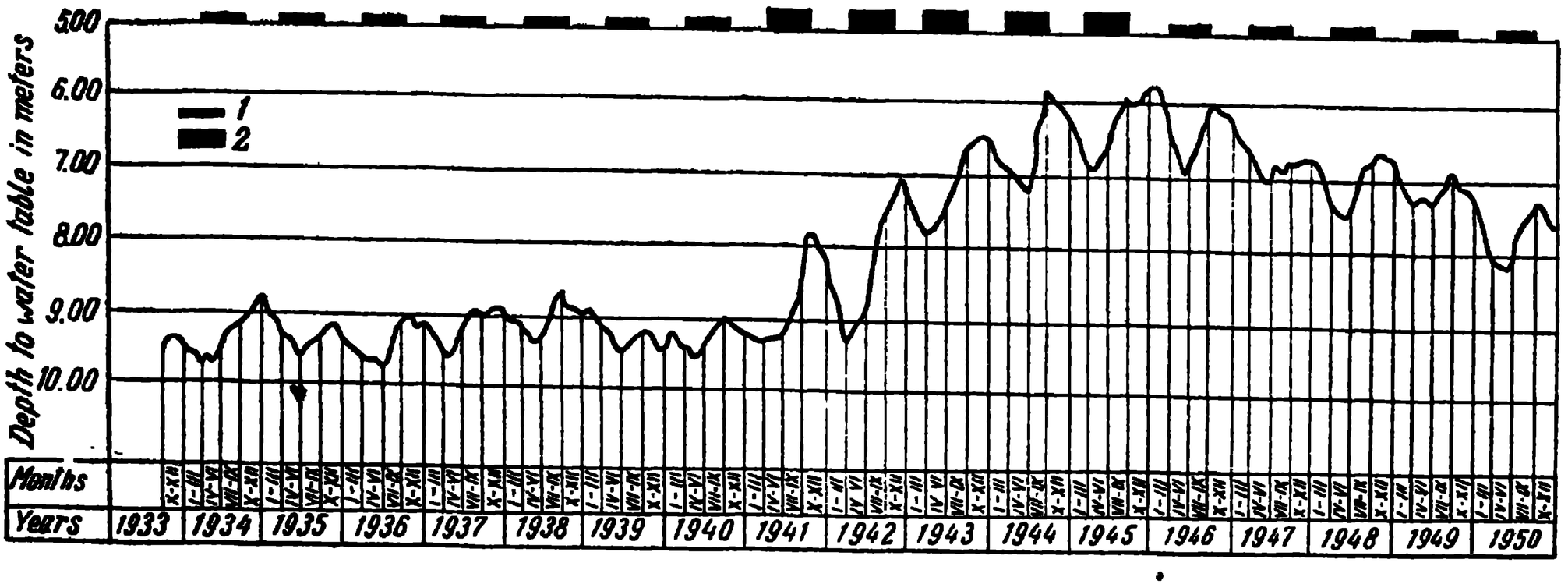

Fig. 16. Free ground water fluctuations under the influence of irrigation in bad lands.

1—period of stable irrigation; *2*—period of additional irrigation.

fluence exercised by irrigation on free ground water regimes (Fig. 17).

Changes, for many years running, in the level of the water table as testified to by field inquiries, are largely caused

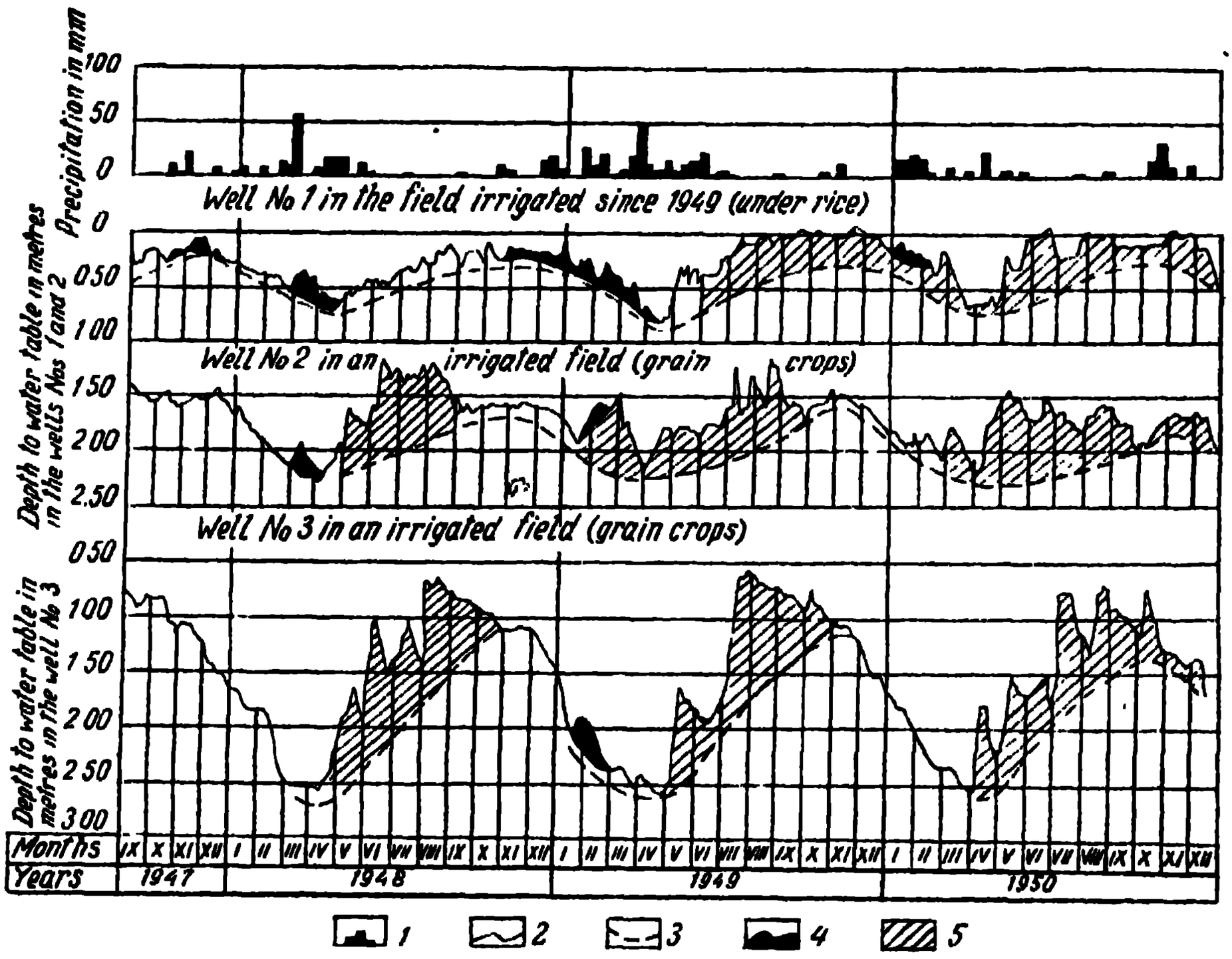

Fig. 17. Chronological charts of fluctuations of free ground water levels along a line of observation wells, showing factors of the free ground water regime.

1—atmospheric precipitates; *2*—curve of free ground water level; *3*—curve of fluctuations of ground water level showing probable trends under the influence of a natural regime of water flow; *4*—fluctuation of ground water level as affected by precipitation; *5*—fluctuation of ground water level as affected by irrigation water.

by water delivery to irrigated land. This effect of artificial factors on such protracted regimes of unconfined waters is obscured in districts served by irrigation systems not provided with specially constructed water intakes or spillways. A direct water intake from a river creates the impression of a natural influence (river discharge) on the long-term regime of ground waters; actually, this is true only for a comparatively narrow belt within a zone under the immediate control of the river. Apart from water de-

livery, long-term variations in the water table may be due to repair of existent, or the construction of new, drainage and collector systems, rationalization of water supply, changes in area of land under cultivation, introduction of gravity irrigation in place of the water-raising wheel (noria), etc. Therefore, to arrive at a proper evaluation and analysis of the ground water regime under given conditions, of major importance (parallel with observations of ground waters) is the timely collection of information on: operation of irrigation systems, reclamation and irrigation in oases, afforestation, areas under agricultural crops and their nomenclature and distribution (particularly rice, because of features peculiar to its watering), irrigation methods, crop yield, etc.

The chemical regime of free ground waters occurring at shallow depth is likewise distinguished by features of its own. The freshest unconfined waters (with a solid residue ranging from 1-2 to 5 grams per litre) accumulate in the central part of irrigation systems having the largest supply. Waters of a higher degree of mineralization (with a solid residue up to 5-10 grams and more per litre) are found in the rear of the irrigation system. Correspondingly, the chemical regime of ground waters is relatively stable in the central part but very variable at the oasis periphery, this being also true with regard to the range of fluctuations in the level of ground waters.

An opinion as to whether the land has improved or not after intensified irrigation, may be rendered only after a comprehensive evaluation of the regime of the level and mineralization of the ground water.

Available facts indicate that prior to irrigation of the Golodnaya Steppe the mineralization of its ground waters was relatively low (the solid residue comprising 4-7 grams per litre) and that time altered the situation very little. This state of affairs prevails even now in the virgin steppe. Mineralization of ground waters during irrigation at first experiences a sharp and continuous rise, followed by a change in the regime. In some areas the trend is towards reduction in mineralization through desalinization of the soil, and through desalting of ground waters by additional layers of filtration. In others, these changes are expressed by a wide

degree of seasonal mineralization, due directly to irrigation. The last case is more typical. Thus, one of the main features peculiar to irrigated regions is a mosaic distribution of free ground waters according to their degree of mineralization and hydrochemical regime. The latter varies for: a) areas in the proximity of main supply and distribution canals, b) irrigated areas beyond the influence of main channels and their distribution system, and c) non-irrigated areas, i.e., those outside the influence of main channels and their distribution lines.

Belts running along main and distribution channels are noted by the existence of temporary lenses of soft desalted phreatic waters that overlie those with a high degree of mineralization. This desalted zone is commonly from 15 to 50 and more metres wide. The composition of the desalted waters is similar to that of irrigation waters, differing from the latter by its higher sulphate content.

The hydrochemical regime of the upper layer of water occurring under irrigated land outside the influence of main and distribution channels is distinguished by its high dynamic quality and wide range of variations in the total degree of mineralization (from 0.6 to 25 grams per litre).

Typical for shallow occurrences of ground water is their sharply pronounced mineralization with predominance of sulphate compounds leading to the accumulation of gypsum. The powerful effect of irrigation is felt in changes of chemical composition of ground waters, principally with regard to cations. Desalted sulphate phreatic waters have a prevalence of calcium and magnesium cations. On the other hand, sulphate waters with a high degree of mineralization are distinguished by the presence of natrium and magnesium. As to anion content, changes are noticeable chiefly in the chlorides.

C) RECOMMENDATIONS FOR THE DISTRIBUTION OF OBSERVATION POINTS FOR THE STUDY OF THE PHREATIC WATER REGIME IN IRRIGATED REGIONS

The ultimate purpose of our investigation, that is, to determine the elements of the water balance and anticipate the regime of ground waters, should be borne in mind in

the distribution of a network of observation points on irrigated territory.

Let us consider two cases: small irrigated areas, and large irrigation regions such as the Kura-Araks Lowlands, the Ferghana Valley, etc.

In a separate area of irrigation, investigations involve the selection of a test plot and an observation line that would embrace typical hydrogeological and geological conditions for the given region.

When selecting an observation line, the geology and hydrogeology of the land block should be thoroughly investigated. This includes: lithology of the rock, geomorphological structure, microrelief, depth and nature of ground water occurrences and their intake and drainage areas, and the character of natural depression curves. In order to do this, a map as well as hydrogeological profiles should be available, embracing the given land and the valleys of adjoining rivers.

To make the final choice of observation lines a field survey should be carried out.

Observation lines should be located on one side of the watershed, following the ground water flow and should reach the river where the hydrometric station is to be established. The number of observation lines depends upon the size of the land and the heterogeneity of its geological structure. With a simple structure and a small area to be irrigated this number may be limited to two lines; one should bisect the given area, while the other should run parallel with the first, outside the boundaries of the given plot (but not over 1-2 kilometres away). Comparison of information relative to the regime of ground waters obtained from these observation lines will reveal the role of irrigation in the formation of the regime.

Should the given plot not cover the whole of the land between the river and the watershed, borings must be sunk along the line not only within the boundaries of the area to be irrigated, but also below and above it (Fig. 18). The total number of observation wells in the line should be about 8-15, depending upon the length of the latter.

To determine the direction of the observation line as dictated by the direction of ground water flow it is recom-

mended to sink borings at the apexes of an equilateral triangle with sides comprising 250-300 metres (Fig. 18). Borings are then drilled parallel with the flow.

The depth of bores is determined by the depth at which the water-bearing formation occurs, as well as by the lowest level of ground water during subsided periods, borings being sounded no less than 3-4 metres below that level.

To fathom the depth and circumstances of occurrence of the underlying watertight bed, several borings should be sunk down to reach it.

Borings are to be provided with filters.

When irrigating large land blocks the layout of the network of observation points should be chosen along lines traversing basic geomorphological elements of the structure in directions typical for the latter (regional transverse sections). In the zone of piedmont trains and plains, the direction of observation lines in valley trains should coincide with ground water flow. The principal line of observation wells should run approximately along the axis of symmetry of the valley trains. Should the structure of the valley train be too complex or too large, supplementary lines may be run which would then cross the wing areas of the valley train and enter intercone depressions.

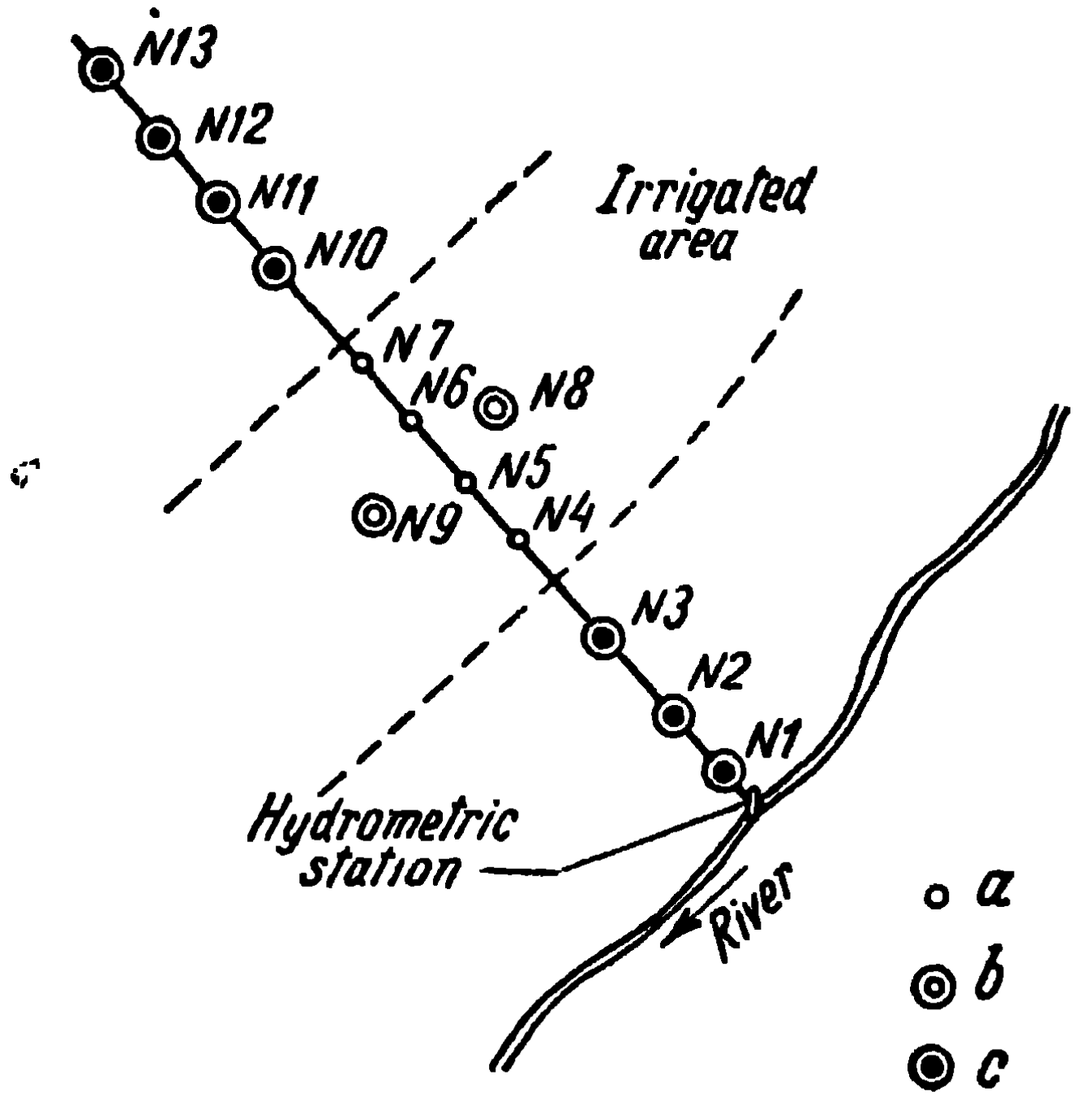

Fig. 18. Distribution scheme of observation wells on the slope of a river valley or wide watershed.

a—observation wells in the irrigated area; *b*—observation wells for determining the direction and shape of free ground water flow; *c*—observation well situated beyond irrigated area.

Alluvial valleys should be crossed by observation lines in a transverse direction (perpendicular to the river). When mountain rivers enter intermountain areas and form valley trains, it is advisable that the lines passing through the al-

luvial valley should be extended so as to also traverse the valley trains. Wherever possible the same transverse sections should be extended up to the mountain and submountain region.

On plains the observation lines should run perpendicular to the river. A line starting from the river should cross the entire oasis and terminate in the adjoining desert.

Observation posts entering into the system of regional lines may be of two types: individual points and groups of points. The latter are in their turn classified as either the linear type (transverse sections towards large canals and collection areas, or rivers crossed by an observation line), and the triangular kind. Observation posts at the apexes of the triangle may be recommended in areas where the movement of ground water undergoes sharp changes. Such places are usually found either along the riverside belt, or on the slopes of a depression flooded periodically by outflows.

The number of observation points and their spacing are determined on the basis of hydrogeological and reclamation divisions of the territory and with the aim of investigating all sections of the area possessing typical hydrogeological and water supply features.

Within the boundaries of each regional observation line typical sections with two observation points should be included. One of these should be located directly on the field to be irrigated, and the other within the general territory but as far as possible from the proposed irrigation channels and irrigated fields.

The necessity of establishing such observation points becomes clear if one considers that the average annual or seasonal level of ground waters depends upon irrigation peculiar to each given year or to each particular area, i.e., on the number of cycles and on the rate of irrigation, all of which is not constant for all years. This makes it difficult to compare average levels of ground water for a series of years even at one and the same observation point, not to mention the nonuniformity of data coming from different points. Furthermore, irrigation peaks frequently obscure the changes in seasonal fluctuations of the ground water table.

Apart from observation points forming a portion of regional lines, a number of supplementary posts beyond the lines should be plotted to elucidate the regime of ground waters occurring in areas presenting hydrogeological interest and possessing considerable national economic importance.

It is advisable to arrange the bores in groups along the vertical cross-section, combining them with those plumbed along general observation lines for hydrochemical surveys.

For proper control of free ground waters with reference to land reclamation and more effective melioration planning it is extremely important that the dynamics of water level and general mineralization of ground waters be observed by means of a more frequent layout of observation posts than those of the basic lines provided by the government.

The above investigations should be performed directly by governmental departments in charge of water resources, whose duties also include the annual compilation of maps showing depths of ground waters during maximum and minimum periods, and of charts illustrating the total mineralization of ground waters during the months of October and May (these months being chosen to take advantage of analyses for the purpose of washing saline soils and correcting the time and rates of irrigation during vegetation periods).

It is the duty of hydrogeological stations to render systematic aid to governmental departments in all matters concerning correct placing of individual points of the observation network, analysis of the regime of ground waters, and the selection of methods for compilation of the said maps. Particular care should be given to maps illustrating the total mineralization of ground waters; for these will be of no value unless due consideration is allotted to existing specific hydrochemical conditions.

It should not be forgotten that the actual worth to the national economy of regime forecasts and other data compiled by hydrogeological stations in irrigated areas will be greatly enhanced if this material is founded not only on the work of state basic networks, but also on that of a dense system of melioration control stations.

5. THE STUDY OF GROUND WATER REGIMES IN REGIONS UNDERGOING DRAINAGE OPERATIONS

The principal problem of swamp study is to establish their water sources.

From this it follows that the main points of consideration in the study of ground waters of land to be drained should be:

a) ascertaining swamp types according to conditions of recharge;

b) studying the regime of ground water fluctuations responsible for the swamp's watering;

c) inquiring into the chemical regime of the waters that feed the swamp;

d) establishing the relation between the regime of ground waters and the factors influencing them.

An all-embracing solution of these problems should form the cornerstone of rational meliorative measures ensuring the most effective economic utilization of swamped land.

A) CLASSIFICATION OF SWAMPS ACCORDING TO CONDITIONS OF THEIR WATER SUPPLY

We are all aware that swamps extend over various geomorphological elements, and that not infrequently adjacent swamps differ strongly in the annual character of their plant associations and degreo of watering. Numerous investigations have established that distinctions in swamp types are explained, in the main, by the regime of waters feeding them.

Therefore, the first thing to do when planning observations of ground water regimes in regions of swamp reclamation is to establish the types of swamps being dealt with.

The following four types are met with in swamp drainage:

1. Flooded swamps with surface (washed on) feed; they are episodically flooded by rivers during high waters and enriched with mineral silt precipitated from the water; they possess diverse grasses.

2. Swamps with hard water recharged by phreatic sources and seepage of mineralized deep (confined) underground waters have hyphae mosses and a variety of grasses.

3. Swamps with soft water from underground sources; sphagnum mosses with a variety of grasses.

4. Swamps fed by precipitation; sphagnum mosses, cranberry growths, etc. This classification corresponds to definite geomorphological and hydrogeological conditions outlined in Table 7 and illustrated by Fig. 19.

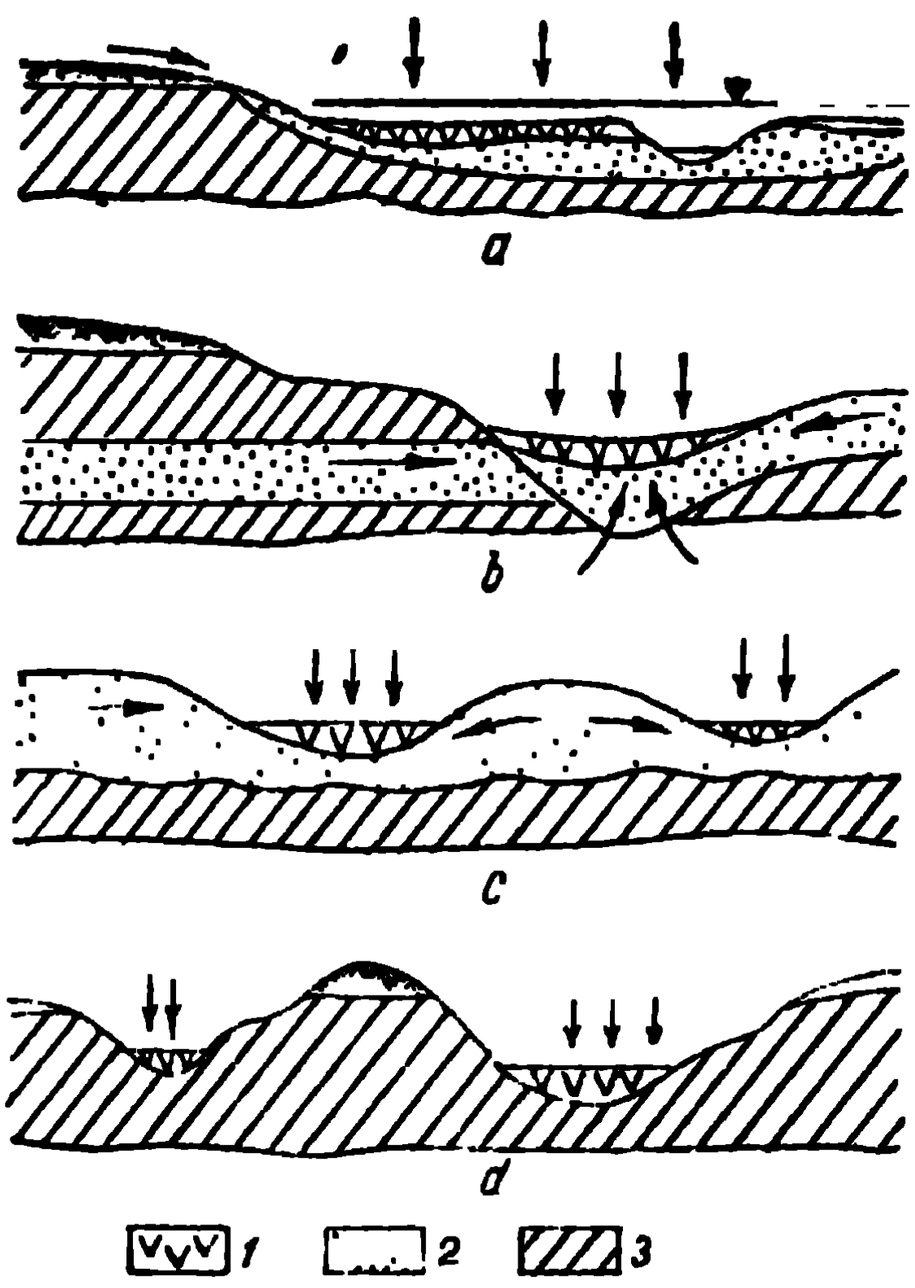

Fig. 19. Scheme of hydrogeological swamp conditions.

1—peat; *2*—sand; *3*—impervious rock (clay, pebbles, boulder loam, etc.).

Available data gleaned from the study of the regime of ground waters in swampy regions prove that changes in ground water level and chemical composition for the above types are subject to various natural laws.

The level of ground waters within the boundaries of *swamps of the first type* whose principal water sources are derived from high flood levels of rivers and lakes depends exclusively upon the hydrological regime of the latter.

Table 7

Types of swamps	Geomorphological elements peculiar to swamp occurrence
I	Low river and lake terraces (Fig. 19, *a*)
II	Hollows along the outer zones of confined water wedges or where "windows" exist in impervious rock underlying the swamp (Fig. 19, *b*)
III	Depressions in flat water-divides formed by surface sandstones of considerable thickness (Fig. 19, *c*)
IV	Enclosed depressions in impervious rock in regions of terminal and bottom morainic landscape (Fig. 19, *d*)

The degree of such influence increases with high flood intensity and the duration of subsidence.

Furthermore, fluctuations in the level of ground waters are appreciably affected by: the distance of swamps from rivers and lakes, their relative elevation over low water and average high flood, as well as by permeability of swamp deposits and underlying strata.

Due to periodical influxes of fresh high waters, changes in chemical properties of ground waters in this type of swamp are commonly of small significance and are revealed only by means of a detailed hydrochemical analysis.

The regime of ground waters in the *second type of swamp* that takes its major supply from deep waters is directly dependent upon underground piezometric level within the zone of upward leakage into unconfined waters, as well as upon inflow intensity towards the swamp. Swamps of this type, as a rule, possess the largest volume of water and their reclamation presents the greatest difficulties. Their level of ground waters is usually very stable, being subject only to small piezometric surface vacillations of deep waters penetrating into the swamp area. The chemical properties of their ground waters are ordinarily closely allied with the mineralization of confined pressure waters and may therefore vary considerably.

The regime of ground waters in the *third type of swamp*, whose principal supply comes from phreatic sources in surface sediments occurring on the slopes of swamp depressions, is usually closely connected with climatic factors. In such swamps fluctuations of ground water level are directly related to precipitation, intensity of infiltration into the cover sediments, and subsequent underflow of the swamp area. The range of instability usually reaches a substantial magnitude in the course of the year (up to 0.5-1.0 metre and more) and is regulated by variations of ground waters in the cover sediments.

The chemical content of these underground waters is usually subject to great irregularities occurring in the course of the year and depends upon changes occurring in ground water reserves. Frequently the processes of mineralization of ground waters in swamps of this type tend sharply towards continental salinization.

The water supply of *swamps of the fourth type* is drawn from enclosed depressions in impermeable rock and originates exclusively from atmospheric precipitates; changes in ground water level and the volume of swamp watering are directly allied to climatic factors. Here the range of vacillations of ground waters exceeds that of the other swamp types (up to 1-1.5 metres and more) and is of a strongly pronounced seasonal character.

Changes in chemical properties of ground waters are quite negligible. The total mineralization is as a rule considerably lower than in the case of the preceding types.

Types of swamps are classified with the aid of a regional field survey. In large regions the scale to which such a survey is drawn should be not smaller than 1 : 100,000, and for individual swamps not less than 1:50,000. The resulting document will serve as a geologo-lithological map with the whole range of swamps and their water content plotted on it.

The features enumerated above predetermine to a certain measure the specific methods to be applied to their study.

Of particular importance in regions of shallow ground waters where their regime is dependent primarily upon climatic factors (precipitates, evaporation, etc.) is the study of the dynamics of heat and moisture within the zone of aeration, for it is well known that fluctuations in air pressure within this zone, as well as capillary phenomena, often distort the true picture of a wavering ground water level. Of no less importance for such districts is research into the laws governing the migration and transformation of various salts in the soil and underlying ground.

Where the free ground water regime is dependent upon the hydrology of open waters (rivers and lakes), a parallel examination of their levels and the level of ground water is a major item in the method of study.

In regions where phreatic behaviour is affected by confined waters of underlying acquifers, a decisive point is the determination of piezometric levels and water permeability of the rock in the zones where confined waters move upward to the phreatic layer. The method of comparative evaluation of chemical properties of ground waters should be used extensively to determine the areas of active hy-

draulic connection between confined and unconfined sources within the entire region where hydrology should indicate such a link.

When investigating the regime of ground waters in swamps inquiry should also be made into permeability, water yield and maximum moisture capacity of the ground; this will be needed to carry out mathematical analyses of the hydrodynamic influence of rivers, lakes and drainage systems on changes in ground water level and to foretell the regime of the latter.

B) THE STUDY OF LEVEL FLUCTUATIONS OF FREE GROUND WATERS AS A FACTOR DETERMINING THE WATER CONTENT OF SWAMPS

We have already noted that ranges of fluctuations in the level of ground waters in bog sediments occurring under equal climatic conditions may vary widely, depending upon types and location of swamps. In this regard the selection of sites for the observation of the ground water table is of first-hand significance. To this we must add that observations should embrace all geomorphological elements, both within the limits of the swamp and at its periphery, with account taken of water feed conditions.

Where swamps cover river valleys and lake terraces, observation points should as a rule be distributed along transverse sections so that the results of investigations may be used for determining:

a) the zone of influence of flood water on the level of ground waters, and

b) amplitude of fluctuation in ground water level as affected by changes in level of rivers and lakes.

In this case a hydrometric station in the observation line is absolutely indispensable. The depth of observation wells should be determined by the possible range of fluctuations in rivers and lakes and the general hydrogeology of the given territory. Borings executed for the study of the ground water regime in bog sediments should reach the underlying impervious bed, while those intended for clarification of the interrelationship of phreatic and

underlying confined waters must be sounded several metres into the pressure aquifer.

The principal aim in studying ground water regimes in swampy regions situated within zones of confined water seepage is elucidating the part which these waters play in the water content of the bog. In such cases observation posts should be located to embrace the peripheral swampy zone noted for the occurrence of confined waters and also include the zone of seepage to free ground waters and the area of total swamp extension.

In instances of swamps resting on surface deposits of good permeability, observation borings should follow the supposed underflow of free ground waters.

In regions where bogs are situated in depressions of impervious rock the bored wells should be confined within the boundaries of the swamp area, some being sounded into the mineral foundation of the swamp, others into bog sediments somewhat below low-water level.

To establish the relation between fluctuations in the level of ground waters and climatic factors a systematic supply of information from the nearest meteorological station is required, including data on precipitates, air temperature, barometric pressure, relative and absolute air humidity, winds and evaporation.

In the absence of a meteorological station in the vicinity proper, meteorological observations should be organized on the spot.

C) THE STUDY OF THE CHEMICAL REGIME OF WATERS FEEDING THE SWAMPS

Bog waters are in the most intimate chemical relationship with peat deposits.

The prime factor determining both the degree and type of peat enrichment with mineral components is the mineralization of waters feeding the swamps. Moors fed principally by precipitation contain soft ground waters with an acid reaction. Forest (transition type) swamps commonly possess a predominance of hard waters. The diversified chemism encountered in ground waters of lowland swamps

inundated by the high flood of a river depends upon the degree of its dilution with waters of the latter.

A very important prerequisite in the chemical formation of ground waters in regions of swamp development are the surface and undersurface flows which determine the leaching of water-soluble substances from bog deposits in some places, and their accumulation in others.

From all that has been said it is now clear that the various types of swamps are very closely connected with primary mineralization of underground waters feeding them. Under specific swamp environment, mineralization of underground waters may further change very measurably and in the most varied ways. These chemical changes of ground water coming in contact with bog deposits may either occur from desulphurization associated with biochemical processes taking place in the silt sediments, or from adsorption of a number of usually scattered elements, etc., all of which alter the chemical type of the water, and which may have a very appreciable effect on the choice of agricultural methods in the reclaimed swamps.

When analyzing the chemism of ground waters in swamp areas, particular care should be allotted to establishing the aggressive (corrosive) character of the waters and the presence of scattered elements therein, this being both of theoretical and great practical importance.

Of equal importance in swamp observation are: uniformity and completeness in methods of chemical analyses of individual components; choice of site for water sampling and its coordination with the most characteristic periods of ground water level as affected by climate or drainage.

D) RELATIONSHIP BETWEEN THE REGIME OF GROUND WATERS AND FACTORS INFLUENCING IT

Timing possible changes in swamp ground water regimes is the ultimate purpose in the study. It is quite clear that this may be achieved only when a definite relation between level fluctuations and active factors is established.

To accomplish this, swamps must be classified in each individual case according to water feed, and only then may a quantitative study be undertaken of all time factors

and their relationship to the regime of ground waters. This relationship may be found only by comparing long-term observation data and by determining the stable regularities existing for definite periods of the year and for numbers of years.

Information necessary for this must be derived from observations of vacillations of ground water level, amount of precipitates, swamp surface evaporation (including transpiration), run-off, air temperature and barometric pressure. A quantitative conclusion on the influence of these factors may be arrived at by calculating the non-equilibrated flow of ground waters by means of the method of finite differences suggested by G. N. Kamensky in 1940 and 1943.

For these computations it is necessary to determine the coefficient of filtration for different types of grounds and peats (by test expulsion, as well as by recording the duration of water recovery after pumping), water release capacity and saturation deficit in the zone of table fluctuations.

6. THE STUDY OF THE REGIME OF FREE GROUND WATERS IN RELATION TO CROP SHELTER-BELT AFFORESTATION

Prior to discussing ground water regimes in connection with crop shelter-belt afforestation, a few words must be said about the general influence of forests on ground waters.

At present the importance of forest belts in ground water recharge in steppe and forest-steppe zones has been firmly established. This has been proven, in particular, by many years of observation of surface run-off and ground water regimes in the Kamennaya Steppe, first undertaken by the eminent Russian scientist V. V. Dokuchayev.

Research into the ground water regime of the Kamennaya Steppe and a number of other regions permit us to arrive at the following conclusions regarding the part played by forest belts in arid regions.

Forest belts change microclimate in favour of ground water accumulation. A sharp decline in wind velocity leads to a noted diminution of evaporation. With an in-

crease in the velocity of the wind the value of forest belts as windbreakers grows.

Forest belts retain nearly one hundred per cent of snowfall. Observations conducted for this purpose at the Kamennaya Steppe station have shown that the annual snow cover in the forest zone comprises 66-200 centimetres as against a bare 14-34 centimetres in the open steppe.

The orientation of a forest belt is a decisive factor in snow accumulation. Maximum accumulations are found in belts located perpendicularly to the wind. There is 1.5 times more snow in Kamennaya Steppe shelter belts running from west to east than in those stretching in a north-south direction.

These belts contribute to a sharp reduction of evaporation from the surface of the soil not only during hot seasons but also in relatively cool and humid periods.

A considerable role in the reduction of soil evaporation is likewise played by the forest ground litter, which reduces cooling and subsequent freezing of the soil in winter and facilitates imbibition of water in the spring when the snow melts.

Woods decrease the range of fluctuations in soil temperature. Under the cover of the forest, melting of the snow proceeds at a slower pace than in the open, and this likewise reacts favourably on intensification of the spring moisture infiltration.

Forest belts are conducive to better percolation not only owing to reduced evaporation losses but also through diminished surface run-off. Thus, after afforestation of only 6% of the catchment area in "Forest Ravine" at the Kamennaya Steppe station, run-off was reduced by more than 100%. At "Selektsentrovskaya Ravine" in the Kamennaya Steppe, where afforestation comprised only 18% of the area, run-off during recent years of observation has become almost nil.

Forest belts exert a marked influence over the regime of ground waters.

According to information furnished by G. F. Basov in 1948 and 1949 for the Kamennaya Steppe territory, there was a substantial rise in spring ground waters in the forest belt and a lesser rise in clearings, while in the open steppe

it was quite insignificant (Fig. 20). During the vegetation period there was a sharp drop in the water table under the forest belt, the drop beneath the clearings was much less pronounced, while in the steppe the range of fluctuations was relatively negligible.

Forest belts in the steppe and forest-steppe zones aid in the recharge of free ground waters mainly through snowfalls, rainfall being of smaller importance since the bulk of it is lost through evaporation or used up by plants during vegetation. Phreatic recharge allied with tree activity proceeds directly under the forest belt and in the immediate adjoining steppe.

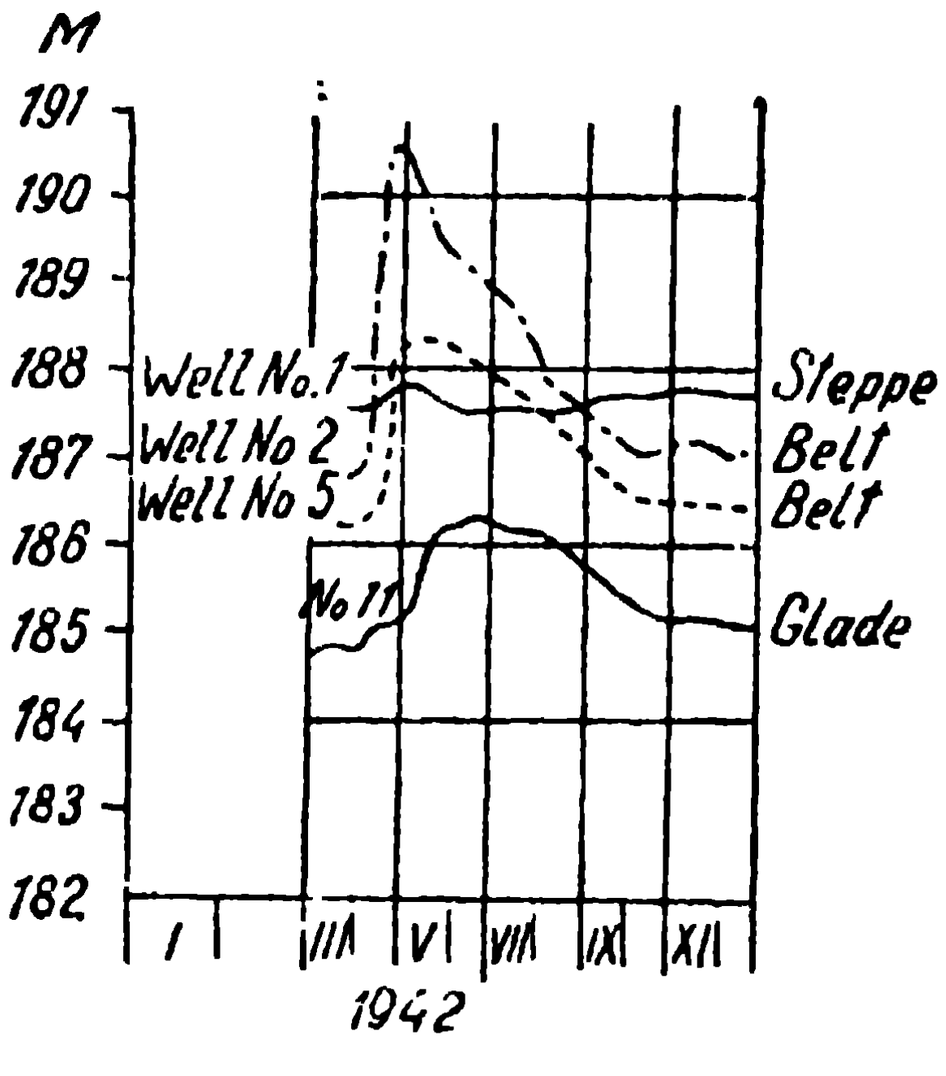

Fig. 20. Levels of free ground water in steppe and beneath forest belts.

Another role is played by crop-protective afforestation in semi-desert and desert regions. One of its principal purposes there is the prevention of possible salinization of the soil due to ground water rise. During irrigation, transpiration promotes lowering of the water table along the irrigation channels, a process which was observed, for example, in the Golodnaya Steppe.

Marsh reclamation along the Black Sea coastline was effected by planting eucalyptus trees ("biological" drainage).

Forest belts change the microclimate of their own and adjoining areas and affect the macroclimate of large territories when planting is done on a mass scale. The ground water regime is thus placed under the influence of a gradually changing climate, modifications which have as their aim the elimination of atmospheric and soil droughts.

Particular attention should be called to the fact that the influence of forest massifs upon the phreatic wa-

ter regime is somewhat differing from that of forest belts.

Massive forests, just as forest belts, transfer surface waters down to the free ground water zone and absorb run-off from neighbouring elevated unforested areas. Forest massifs do not limit themselves to reduction of their own surface run-off, but also regulate run-off of adjoining unforested land.

As distinct from forest belts where a great amount of snow is carried along the ground from the steppe by storms, the accumulation of snow in broad forests is due to direct snowfall. The types of trees in a forest belt bear no great importance for snow accumulation, while those in a forest massif are significant; a substantial proportion of the snow-fall is retained by the tree crowns and is subject to evap-oration. Leaf-bearing trees have been found to be the most favourable for snow accumulation. Fir trees retain about 25% of the snow on their crowns, pine trees—15%. Snow held in this way evaporates and reduces the precipitation reaching the soil.

V. I. Rutkovsky noted in 1948 and 1949 that in regions with deep-lying water tables (forest-steppes and steppes) the positive effect of standing timber on ground water ac-cumulation is greater than where the water table is near the ground surface.

Owing to good infiltration, massive forests growing on sandy soils lay up huge water reserves in wet years. In dry years these resources are gradually drawn upon for underflow and evaporation.

Forest massifs growing on loamy ground contribute to moisture replenishment only in the spring, while in sum-mer due to transpiration, the level of ground waters in the woods is lower than beneath ploughlands.

As to study methods of ground water regimes, the hydro-geological station working on crop-shelter afforestation should concern itself principally with regimes in forest belts, forest massifs, and adjacent areas and embrace vari-ous climatic, geological and hydrogeological environments. Likewise of no little importance is the question of tree growth, to be discussed later.

Studies should include all elements (water level, tem-perature, chemical properties) and be accompanied by

investigations of moisture and temperature in the zone of aeration.

To discover the role of afforestation as a factor influencing the water regime, observations of the latter should include a zone of both forest belts and adjoining steppe existing under similar hydrogeological conditions.

Due consideration should be given to tree species, depth of the root system, and the age of the trees.

Our ultimate goal is to establish the balance of free ground waters; of particular importance in this regard is the moisture balance in the zone of aeration, since this constitutes a connecting link between the atmosphere and free ground waters. No less attention should be paid to freezing and thawing of the soil as determining the infiltration of precipitation.

Since the role played by shelter belts rests essentially upon the climate, geomorphology, geology, and hydrogeology of the locality, observations should be conducted in representative areas with a view to applying the result to specific geographic regions.

Therefore, the laying out of observation posts should be preceded by a geological and hydrogeological examination of the given territory and an inquiry into conditions of tree growth.

Earlier observation data should answer the following points:

1) circumstances attendant upon the given water-bearing formation;

2) the thickness of the zone of aeration, its lithology and granulometric composition;

3) the nature of the soil cover and its thickness;

4) the topography and microrelief of the territory under investigation.

Studies pertaining to tree growth under conditions of both belt and massive forests should be conducted on the basis of the work of agricultural and forest amelioration stations or individual local investigations.

The following points are to be established during the inquiry:

1) structure of individual belts (thinness);

2) width of belts and intermediate areas;

3) types and age of trees;
4) height of belts;
5) depth and distribution of root systems and ratio of depth of ground water table to root systems;
6) disposition of the forest belts with regard to direction of ground water flow;
7) the same in respect to direction of dominant winds.

Furthermore, the following should also be made clear:
1) area of forest massif;
2) tree density.

The distribution of ground water regime observation posts in large state-owned forest belts should be somewhat different from that of local belts.

1. For large state-owned forest belts consisting of one or several forest zones ranging from 30 to 60 metres in width and running across extensive areas, observations should be conducted on a number of profiles (cross-sections).

These profiles must give sufficient material on ground water regimes under differing climatic, geological, and hydrogeological environments.

Observation profiles should cross the wooded belt, intermediate bands and the steppe. Since the effect of tree planting on phreatic water will be greatest in the belt vicinity, this latter should have shorter bore spacing intervals than in the zone beyond.

The number of points along each profile should be determined according to the width of belts and intermediate areas. A profile traversing a zone of several individual belts, each 60 metres wide, with intermediate areas ranging from 100 to 300 metres should have observation bores sunk in the following manner: the centre of each constituent belt, its edges and the intermediate areas should have one bore each. The steppe beyond either boundary of the belt should also be bored (one or two wells within the zone of influence of the belt and one or two outside this zone).

A detailed study of their ground water regimes should be made in those parts of state-owned forest belts that are most representative geologically and hydrogeologically. (Water balance plots.)

2. For local forest belts, observation wells are also plotted along profiles. These should be typical with regard

to relief, microrelief and coordination to dominant winds as well as direction of underground flow. Observations must embrace both old and newly planted wooded zones as well as zones of differing structure. Profiles should cleave forest belts, intermediate areas and the territory beyond the influence of the forest belt, that is, the steppe.

Operations embracing the regime of ground waters beneath forest lines planted along irrigation channels should be guided by observation profiles chosen perpendicularly to the latter, bore spacing diminishing as the channels are approached.

In forest massifs there should be several observation profiles traversing the district along lines of varying geology and hydrogeology, and both parallel and perpendicular to the ground water flow.

As already stated, surveys should include both old and newly planted massive forests.

Variations in species and age of standing timber must be taken into consideration in the choice of observation post along all profiles. If the trees are of a uniform kind, the bores should be aligned along the centre of the massif, its wings, as well as beyond the limits of influence of the forested area. "Water-balance" investigation bores should also be sunk.

Surveys along all profiles should include height, temperature and chemical composition of underground waters.

Additional studies at water balance plots should include inventories of free ground waters and moisture within the zone of aeration, and observations of temperatures, freezing and defrostation of the soil.

The inquiry should also include a survey of the following elements:

1) recharge through percolation of atmospheric precipitates (or influx of irrigation waters in irrigated regions);
2) condensation of water vapours;
3) inflow and outflow of free ground waters;
4) evaporation of free ground waters;
5) plant transpiration;
6) variations in moisture content within the zone of aeration.

Methods applied in the study of the balance of free ground waters are discussed in Section 7 of Chapter III.

On crop-shelter afforestation territory special emphasis in the analysis of underground water inventory should be given to transpiration and condensation under the trees with due consideration to differences in transpiration capacity of various species.

In the course of the vegetation period transpiration is the predominant element in the balance of free ground waters.

The study of the ground water regime at water balance plots should be accompanied by meteorological observations.

Parallel with topics concerning afforestation influence on the ground water regime, an examination of microclimate should be conducted, embracing the afforestation territory proper and the zone within its control in the steppe in which the following meteorological elements should be considered:

1) precipitates;
2) wind velocity;
3) air humidity;
4) air temperature;
5) evaporation from the surface of the soil as well as at crown height;
6) condensation of air vapours.

In considering atmospheric precipitation, water reserves of snow and the latter's distribution over the territory should not be forgotten.

Changes in wind velocity due to forest belts cause a corresponding meteorological evolution. Since the effectiveness of forest shelter belts increases in direct proportion to their height, the zone of their effectiveness must be determined in each individual case.

Particular attention should be allotted to the effect of afforestation on surface run-off and the latter's relation to underflow. Increased underflow at the expense of surface run-off represents one of the major aims of tree planting.

Studies of surface run-off should begin directly with the initiation of afforestation. In major valleys and spillways, snow surveys and measurements of overflow must be conducted with due consideration to species of trees,

since this latter greatly influences the amount of precipi tates reaching the soil on the territory of forest massifs. Hydrological surveys should be closely coordinated with those of the regime of ground waters. Hydrological observation lines should be combined with hydrogeological observation profiles.

To reveal changes in underflow, charts with contours of the water table for typical periods should be systematically prepared.

More frequent note should be made of level and temperature of free ground water and moisture content in the zone of aeration during snow melting and vegetation.

To determine the effect of the forest on the chemical composition of underground waters, samples for chemical analysis should be taken in the belt proper, its wings, in the zone of influence of afforestation and the steppe. Sampling should be repeated several times a year.

In the course of chemical investigations, note should be made of possible varied effects of different tree species on the chemical properties of the water, for different tree types require unequal quantities of mineral salts for normal vegetation.

7. THE STUDY OF THE REGIME OF UNDERGROUND WATERS IN CONNECTION WITH HYDROTECHNICAL CONSTRUCTION

Hydraulic structures radically change the regime of underground waters, causing filtration beneath and around dams, backing up within the zone of reservoirs and in some cases a change in flow direction (filtration into neighbouring valleys).

The general problems of underground water regimes relative to designing, construction and operation of hydrotechnical structures are:

1) fixing the exact hydrogeological conditions within the area of hydrostructures and reservoirs;

2) forecasting changes in the regime of underground waters as affected by construction;

3) determining hydrogeological parameters (coefficients of filtration, saturation deficit, water yielding capacity, infiltration feed and evaporation).

The regime at a dam site is a somewhat different problem from that encountered when designing reservoirs. In the former case we are concerned mainly with the effect of the changed regime on the operation of the structure, while in the latter instance the major question is the influence of the reservoir on adjoining territory (flooding by seepage).

This leads us to treat the problems of dams and reservoirs separately.

A) THE UNDERGROUND WATER REGIME AS AFFECTED BY DAMS

The construction of a dam causes two kinds of filtration: beneath its foundation and at its flanking bank abutments; the first is always under pressure, while the second is usually free of it. When the horizon behind the dam reaches its normal level, the flaw beneath the foundation and its principal characteristics (pressure head, discharge) become quickly constant and just as quickly respond to changes of water level in the reservoir due to draw-off, high flood, etc. Forecasting of the piezometric water head beneath the dam is conducted by hydraulic engineers in accordance with formulae for steady flow, due consideration being allotted to the underground dam contour and to anti-filter arrangements.

Filtration at bank abutments (by-pass filtration) develops sooner or later and the time factor here is therefore weighty. For this reason observations of the underground water regime during filling and operation of the reservoir are particularly important. These observations, however, will be effective only if commenced prior to construction, otherwise it will be impossible to determine which changes in underground water level can be ascribed to the dam, and which to natural forces.

To properly distribute observation wells in the area of bank abutments, some idea must be formed as to the possible

size of the zone of by-pass filtration under conditions of steady flow.

Three zones may be chosen on the banks of a reservoir, each having its own regime features of underground waters under pressure conditions developed by the reservoir.

In the area immediately adjoining the flanks of the dam, by-pass begins from the reservoir into the downstream side of the river. This is usually called the zone of by-pass filtration (Fig. 21).

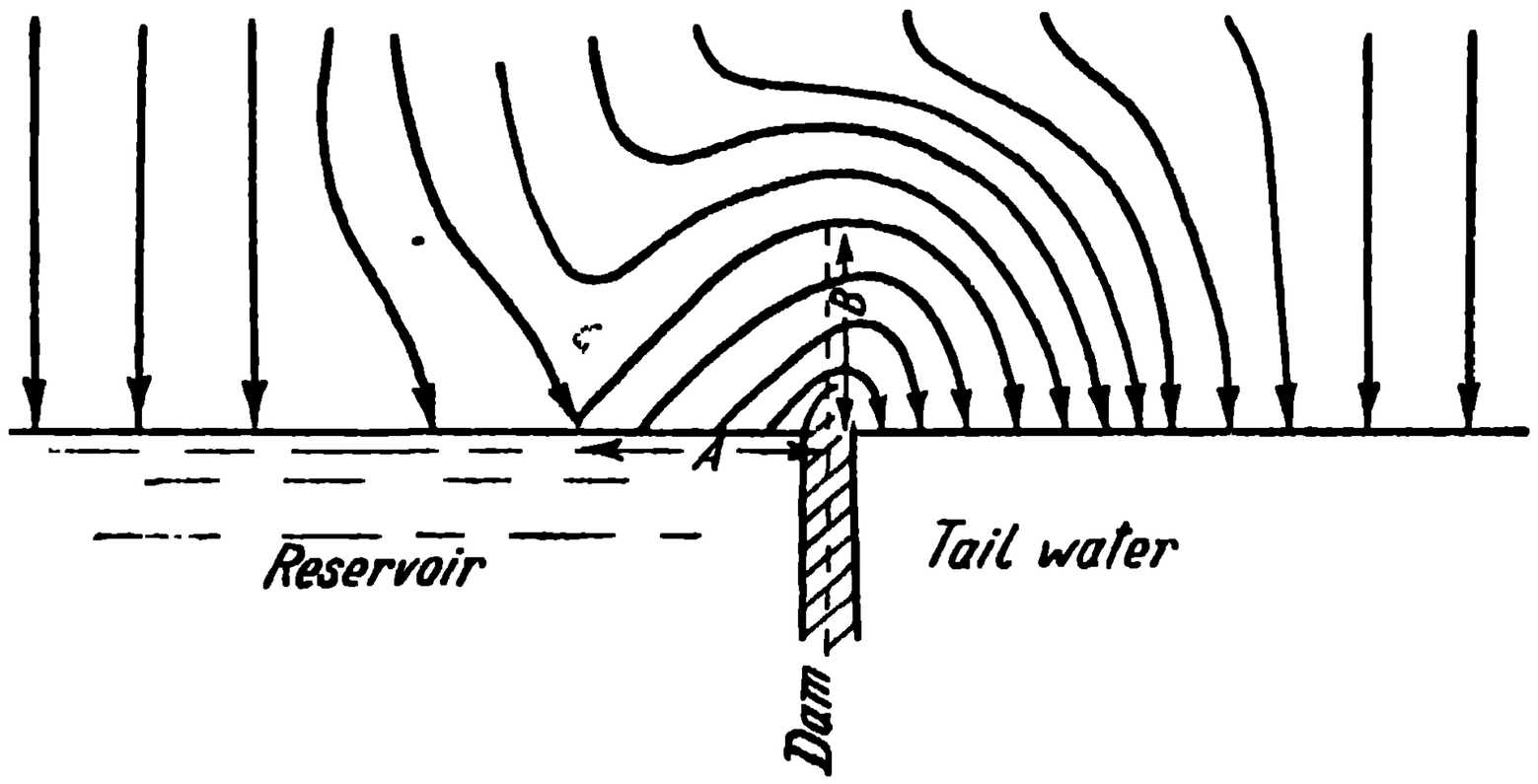

Fig. 21. Scheme of by-pass filtration.

At a certain distance from the dam phreatic flow is no longer affected by tail water and within this zone the flow lines of free ground water differ very little (in plan) from those prior to construction, that is, they are roughly parallel ("plane" flow).

Between the above two zones there is an intermediate area which, though somewhat experiencing the influence of tail waters, actually contains no filtration from the reservoir towards the effluent level.

The boundaries of by-pass filtration are determined by:

a) geological conditions;

b) configuration of the river valley in plan;

c) gradient of underflow within the bank belt.

A filtration area within the limits of a given terrace may be delineated by its width if the terrace is in direct contact with impermeable bedrock. In some cases the filtration zone at the upstream or downstream sides is limited by outcrops of watertight rock at the riverside. In fis-

sured rock the filtration area is often limited by a zone of weathering, etc.

The configuration of the valley is also important. If there is a bend in the valley the amount of filtration in the concave bank will be greater than in the convex.

Of particular significance is the slope of underground flow into the river prior to construction of the reservoir. Other conditions being equal, the greater this gradient the smaller will be the area of by-pass filtration; the underground flow seems to "elbow out" the filtration flow attempting to by-pass the dam. If there is no slope of underground flow, then, theoretically, filtration may take place along the entire banks if, of course, geological structure does not present other obstacles.

The principal problems before us relative to underground water regimes at dam sites are:

a) to establish the relationship between water-bearing formations and the river;

b) to determine the permeability of the rock at the junctions of the dam with the valley slopes;

c) to remove all errors from computations of by-pass filtration.

If two or more aquifers divided by relatively impermeable layers occur at the base of a dam, it is essentially important for the welfare of the latter to establish the degree of interconnection between these aquifers and the river.

Such an interconnection of underground waters with the river is approximately established during prospecting, on the basis of lithologic composition of the rock and changes in piezometric level of the water with increased depth of borings. But this criterion cannot always be accepted, particularly if the bedrock of the valley is hard or medium-hard in a variable-fissure state. Neither are observations of piezometric level changes during drilling always sufficiently reliable, since pressure head in various confined aquifers during the boring process may differ slightly. Furthermore, during boring with a bailer in sandy rock the true level may be obscured by an artificial drop, while in hard rock and with wet drilling the level may rise artificially.

The most dependable data showing the relation between phreatic and river waters when a number of water-bearing strata occur may be obtained by observations of the underground water regime along a transverse line with several groups of wells, each with a filter installed in a definite water-bearing stratum. Thus the number of wells in each group will be equal to the number of water-bearing strata to be investigated: The transverse line should run perpendicularly to the bank of the river; in case of sloping beds, it should also turn across their strike. A hydrometric post must be set up on the river to follow changes in its horizon.

During considerable river fluctuations, such an investigation by means of a system of wells will identify the aquifers responding to such fluctuations, indicate the degree of such response and show which aquifer's regime is independent of the river.

When choosing a dam site an estimate of the permeability of the bank bedrock is very important. But if the banks are high it is sometimes technically difficult to determine the coefficients of rock filtration by means of test pumping; it will be hard to achieve the necessary drawdown of deep lying waters, particularly if the rock possesses appreciable permeability. Observations of the underground water regime may furnish sufficient data for a comparable estimate of areas adjoining the dam with regard to their permeability.

During high waters the fluctuation of the phreatic water table at the river is in the main subordinate to fluctuations of the river's horizon. Infiltration of precipitation is of secondary importance and may be discounted, particularly if the water table lies at deeper levels (five metres and more) in which case thawing waters will not have had time to percolate to the water table during high flood on the river.

By applying the equations for unsteady underground flow it is possible to determine, on the basis of ground water rise, the value of $\frac{K}{\mu}$, i.e., the ratio between the coefficient of aquifer filtration (K) and the saturation deficit (μ). In loose rock the value of μ may be determined directly as a difference between rock porosity and its nat-

ural moisture content before high flood. In hard rock this value is determined by a survey of its fissuring at exposed points, or even better, in a mine. This makes it possible to find the coefficient of filtration of the rock at the points of abutment of the dam and the bank bedrock.

To determine filtration coefficients for comparative lines of the dam, four or five observation wells should be sunk along each line.

Approximate spacing of borings from the boundaries of the high flood area should be:

5*H*	for	1st	bore
10*H*	"	2nd	"
20*H*	"	3rd	"
50*H*	"	4th	"
100*H*	"	5th	"

H (approximate height of flood level) is obtained from available hydrological data.

Water level observations should be made daily during high flood and be accompanied by recordings of water temperature.

Should the mineralization of river water during high flood prove to be essentially different from underground sources, water samples for chemical analysis should be collected every 5-10 days.

Observations of the regime of underground waters for the study of by-pass filtration should be conducted when it is feared that:

1) filtration discharge may represent a substantial item in the total water inventory of the reservoir;

2) the rate of filtration will be so high as to cause suffosion, washouts and rock solution;

3) the gradients of filtration flow in their exit on the downstream side may give rise to (or intensify) landslide phenomena.

The distribution and number of observation bores depend upon the geology and the hydrogeology of the site and the stage of construction designing.

During prospecting conducted for the preliminary design a number of observation wells should be sunk along a transverse cut coinciding with the axis of the proposed dam. During prospecting preceding the stage of working drawings,

when the location and type of dam have already been determined, groups of wells are drilled over the areas of flanking bank abutments and along the upstream and downstream levels. The basic line of bores is to be sunk along the axis of the dam in addition to two parallel lines sounded above and below (Fig. 22).

Distances between the basic and parallel lines are decided according to hydrogeological conditions of the plot. The nearer lines determine changes in the underground water regime within the zone immediately adjacent to the dam where, following the development of backwater, the gradients and velocity of filtration flow attain their highest values. The object of the outlying parallel lines is to give a general picture of by-pass filtration, not only to determine filtration losses but also possible flooding of the banks.

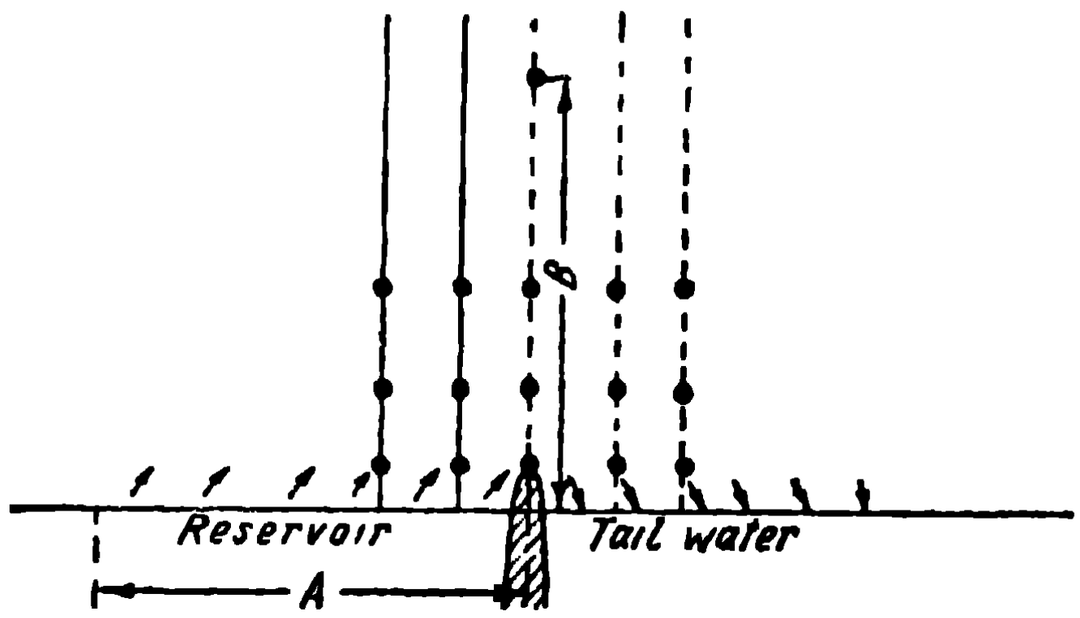

Fig. 22. Distribution scheme of observation wells.

The length of the basic [axial] line of wells is determined by the probable front of by-pass filtration along the extension of the axis. If the proposed dam contacts with an alluvial terrace resting against bedrock of low permeability, this basic transverse cut should cleave the entire terrace. The same is true when the dam contacts hard bedrock whose permeability, subordinate to weathering processes, shows a sharp decline with increased distance from the slopes. In this instance the transverse line should bisect the weathering zone.

If the zone of by-pass filtration is not limited by any particular features of geological structure, the length of the transverse line is to be not less than one half the distance from the bank to a point whose free ground water table is equal to the planned horizon of the reservoir.

The length of the transverse lines running parallel to the basic axis may be approximately one half that of the latter.

When spacing the wells along the basic transverse line, the well nearest to the river should be at the level of normal backwater.

Surveys of the regime of underground waters at flanking bank abutments are to be continued during and after filling of the reservoir. On the basis of these observations, opportune extra measures may be adopted either to reduce filtration (by a cement cut-off) or to safeguard the slopes on the effluent level against landslip (by drainage). Observation of the underground water regime prior to impounding will aid to correctly interpret level changes in the bores occurring during and after impounding, for the reservoir will certainly influence natural factors.

If observations of the underground water regime have as their object the calculation of filtration losses from the reservoir, their duration may be relatively limited (about one year) since filtration flow will lessen in time. On the other hand, if the aim of the investigations is the study of filtration velocity or gradients on the downstream side of the dam, they should be continued until filtration becomes steady, since both velocity and gradients will grow during the period of variable movement. In the latter instance observations may last a number of years. Lastly, if there should be any danger of rock solution, washout of clay in the fissures of the rock, etc., the survey should be continued indefinitely.

Observations of the underground water level are to be performed once in five days just prior to impounding the reservoir, and once a day during and immediately following spring high waters. Daily recordings should also be conducted while filling is in progress and in the course of the following year, and are to be accompanied by temperature readings of the water. When complex hydrogeological conditions are encountered at the dam site (several water-bearing strata), or when there is danger of rock solution by filtration flow or if the waters are found to be aggressive, there should be a systematic chemical sampling of the water at least once a month.

B) THE UNDERGROUND WATER REGIME AS AFFECTED BY RESERVOIRS

A rising water level due to the construction of a dam in a river causes a temporary depression of the ground water table along the reservoir banks to some distance from the dam, a depression which is counteracted by filtration from the reservoir and phreatic inflow from the intake area. In some cases this depression soon disappears and the feeding of the reservoir by ground waters is renewed (Fig. 23, *a*), while in other instances seepage begins from the reservoir into the neighbouring valley (Fig. 23, *b*).

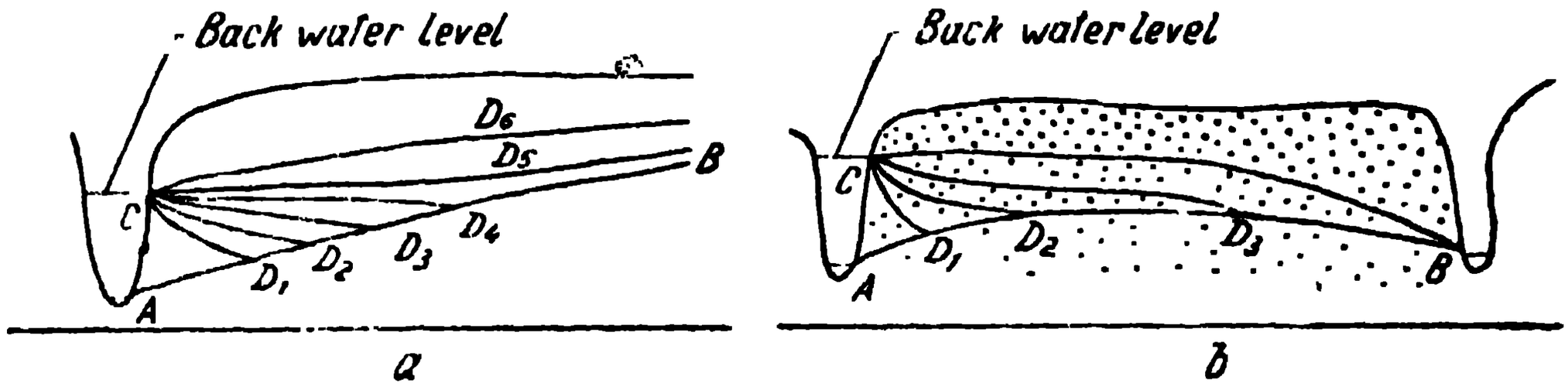

Fig. 23. Scheme showing development of underground backwater.

AB—depression curve prior to development of backwater; CD_1, CD_2, etc.—consecutive positions of depression curve in the process of backwater development.

Typical for the period of backwater development is a constant rise in the level of free ground waters within the entire watershed and a progressive diminishing in speed of this rise. At the same time the ground water level experiences periodic fluctuations because of non-uniform recharge by the annual cycle of atmospheric precipitates. Consequently the progress (rise) of the depression curve is combined with oscillations and the role of the former as a factor affecting the ground water regime relatively diminishes with time, while that of the latter shows a corresponding relative increase. After a suitable interval the rate of rise of the depression curve becomes so negligible that its recording becomes difficult against the background of periodic fluctuations conditioned by meteorological factors. The development of underground backwater may be consid-

ered practically completed when the levels of free ground waters, taken at corresponding points, differ from the depression curve of the "stationary" backwater level by a value comprising less than half of the range of ground water fluctuations in their annual cycle.

The water impounded in the reservoir during high flood is, in one way or another, drawn from in the course of the year, causing a subsequent drop in level. In reservoirs used for irrigation purposes these annual drops may comprise as much as 20 metres and more, variations which provoke corresponding ground water fluctuations in adjoining areas and which frequently exceed those caused by meteorological factors.

Our principal aims in studying the regime of underground waters in bank areas of reservoirs are:

a) synchronization of data obtained through prospect drilling;

b) gathering of information for forecasting changes in the regime of underground waters when these latter are backed by the impounded reservoir.

Prospecting at the sites of large reservoirs is often extended for a considerable length of time—months and sometimes years and it is therefore not unusual that material relative to ground water levels obtained through drilling is differently dated and not comparable. But to forecast the phreatic regime in the course of impounding and operation of the reservoir, data must be obtained pertaining to the subterranean water table during its ultimate period of reduced feed, when its movement approaches a steady flow. Hence water level readings should be brought to their rated values, which may be done by providing part of the transverse observation lines with filter-equipped bores and carrying out systematic observations of the ground water regime along these lines. Let us assume an example.

The water table in a prospect well is recorded on the 1st of November, but the reading required is for the 1st of March of the same year. Let us assume, further, that the water level in the well in which observations are being taken rose 56 centimetres from the 1st of March till the 1st of November. Hence to achieve a rating corresponding

to the 1st of March, all that is necessary is to subtract 56 centimetres from the recorded level.

It should be emphasized that on no account are purely mechanical recalculations of levels to be made, such as by taking "mean" corrected values for the entire area; in each instance actual hydrogeological conditions in the observation wells should be considered.

Phreatic fluctuations along the river-front where high flood is an important prerequisite are governed by other laws than those prevailing at some distance from the river and where the underground regime is affected by meteorological factors alone. The character of such phreatic fluctuations is dependent upon permeability of the rock, geomorphological forces, depth of ground waters and a number of other factors. The duty of a hydrogeologist conducting preliminary prospecting for the reservoir design is to typify geological conditions by the use of data obtained through a comprehensive geological survey of the riverside zone and then to sink lines of bores along each typical area. Corrections should be administered to water level readings in accordance with those registered in observation wells found under similar hydrogeological conditions.

Another purpose of the above observations is to obtain data necessary for time forecasting of phreatic backwater development. These are effected by various methods of calculation based on the theory of unsteady flow—analytical method, method of finite differences, and scale-modelling of filtration with the use of a hydraulic integrator. But in all instances the following values must be known: coefficient of filtration of the aquifer, its saturation deficit, and the amount of recharge through precipitation. These hydrogeological parameters may be determined directly by a survey of the ground water regime and by corresponding calculations based on the method of finite differences.

Observations should be effected along perpendiculars to the river valley, crossing typical hydrogeological areas. The more diverse the natural conditions, the greater should be the number of these lines.

When exploring water-front areas for very large reservoirs the distance between transverse lines should average from five to ten kilometres. In inhabited areas and territories

occupied by industry, mines, etc., the distance between transverse lines should be reduced to about several hundred metres.

To coordinate observations of the ground water regime with river fluctuations, a number of hydrometric stations should be provided for.

The length of transverse lines should be determined by the following considerations: each line should extend from the river to a point situated at such a distance from the proposed reservoir where backwater ends or where the level of the terrain is so high that flooding by seepage is impossible. Backing of water may be limited by contact of the alluvial terrace with impermeable bedrock, by the existence of a river within the zone of backwater, or by an area swamped by free ground waters. In the absence of such limitations the transverse line should be extended to a point at which the stationary backwater level does not exceed one half the possible range of annual fluctuations of the water table (approximately 0.3-0.5 metres).

Observation wells in the transverse line are to be sunk: at a level reached by the river's high waters; at another corresponding to the draw-off level of the reservoir; at an elevation of the normal backwater level of the reservoir, and then every 200-500 metres (depending upon hydrogeological complexity) up to backwater limits.

To determine the geological cross-section for the entire thickness of the aquifer, borings should reach the watertight bed. If the aquifer is of a uniform nature, filters should be placed in its upper third; the length of filters should be not less than 3-5 metres, with the upper limit of their effective length extending 2 or 3 metres below the phreatic low-water table.

In many cases terrace alluvial deposits consist of two formations; an upper, containing rock of relatively low permeability (sandy loams, fine-grained sand), and a lower consisting of highly permeable coarsely graded (sometimes gravel-like) sands. Under such circumstances the lower layer, if its roof occurs below the level of the river, appears to be under pressure, while the upper is relatively watertight. In the lower layer the influence of high-flood water extends to a considerably greater distance than in the

upper formation and with a more pronounced amplitude of level fluctuations. If the ground water regime is not affected by the river but only by meteorological factors, this relation between ranges of fluctuation in the upper and the lower layers is reversed. During the melting of snow or intensive rainfall the rise of level in the upper layer is greater than in the lower, which then assumes the role of a stratum drain.

Because of this strongly pronounced double alluvium structure it is recommended to provide duplicating observation wells. In one, the filter is arranged in the upper layer while in the other it is sunk close to the first in the lower layer.

The problem of determining the source of fluctuations of the ground water table is very important in foretelling free ground water regimes. The reasons for level changes due to high flood in a river have no bearing upon new conditions created by an impounded reservoir; in the latter case, changes of horizon in the river will differ essentially from those existing prior to the construction of the reservoir.

Nevertheless such observations are of very great value, since, by their means and by corresponding calculations the ratio between the coefficient of filtration and the saturation deficit of the stratum may be determined, a point of utmost consequence in forecasting. Recordings of fluctuations of the ground water table as affected by meteorological factors are used to calculate the amount of meteoric recharge, which is also needed for forecast compilation.

Water table observations along the whole line should be made at least once every five days (and daily during high flood) with corresponding temperature readings of the water. If underground and aboveground waters should show a sharp difference in mineralization, reduction analysis sampling should be resorted to before, at the peak of, and after high flood. All such chemical and temperature readings are often a convincing source of information revealing the influence of high flood on the regime of underground waters.

Bore lines should be equipped and begin operation at the very first stages of the programme (preliminary) design

for the reservoir, with further expansion of fixed observation bores during exploratory work required for working drawings. Investigations should be prolonged both during impounding of the dam and the first few years of reservoir exploitation, permitting correction of forecasts of the development of backwater and checking the effectiveness of measures undertaken for the protection of the territory against flooding. Investigations conducted during normal exploitation are also of great value in the designing of new reservoirs which are to operate under similar hydrogeological conditions.

8. THE STUDY OF THE REGIME OF MINE WATERS

A) PURPOSE OF THE STUDY

A study of mine water regimes under various hydrogeological conditions is of major theoretical and practical importance in developing the hitherto insufficiently enlightened problem of anticipating mine floodings.

This problem is of especial value as related to both increasing depth and lateral expansion of the mine. As a rule, water inflow does not remain constant at all seasons of the year, but varies with the amount and character of precipitation. Under certain geological conditions (in karst regions for example) the maximum spring inflow is from three to five times higher than the minimum during winter months. By determining the changes in seasonal mine inflow we may closely establish an interrelation between mine and meteoric waters and ascertain the sources of various aquifer recharge and the part these sources play in the flooding of workings.

As a rule, during the first advance into a mine and its initial exploitation the water inflow is considerably dependent upon the exhaustion of static reserves. But as the depression cone increases, water begins to flow from intake areas of water-bearing formations and the further rate of inflow will then be contingent upon the size of the intake area and the circumstances under which replenishment of underground sources is effected. Should the magnitude of the intake area be limited, or conditions for replenish-

ment be unfavourable, the increase from dynamic sources may be very insignificant. In complicated tectonic zones (as in some regions of the Kazakh Republic, Kuznetsk Basin, Donets Basin, and elsewhere), as the mine both deepens and expands, the general rate of inflow even declines due to exhaustion of static water reserves in small folded structures. But in other cases, deepening and expansion along the strike results in a growing increase of inflow either because of intensified infiltration of aboveground water or penetration from new aquifers.

An inquiry into the mine water regime should not be limited to surveys in the workings, but should be preceded by a series of systematic observations. A special network of bores should be sounded in typical hydrogeological sections prior to the commencement of mining operations. This will expose the dynamics of the hydrogeological phenomena and its subordination to mining operations, to filling of old mined-out workings and to the opening of new blocks. Such comprehensive observations are extremely important in solving the practical problems of exploitation of large flooded deposits.

In recent years Soviet industry, armed with highly developed equipment, has begun working a number of deposits whose complex hydrogeological and geologo-engineering problems have hitherto presented considerable exploitation difficulties. A still greater number of such deposits, prospected or to be prospected and occurring under similar conditions, are to be developed in the very near future.

Effective, profitable mining under such circumstances is possible only by simultaneous operation of several shafts. This means that the sequence of opening each section should be conditioned by the nature of its individual hydrogeological and geologo-engineering requirements and that at the commencement of operations due consideration should be given to the fact that mining and drainage work conducted in one block will facilitate development and drainage in adjacent ones.

From this it is clear that without a study of the water regime a rational solution of the above problems is impossible.

Together with looking into quantitative deviations of water inflow into mines, a simultaneous examination must be introduced of chemical and mineral variations of surface and underground waters, the aim of which should be to clarify the link between various water-bearing formations and aboveground bodies of water and obtain necessary data for an understanding of the drainage influence of mine workings and the routes of underground and surface waters into the mine.

All this will help to solve a number of practical problems such as:

a) forecasting variations in rate of inflow and the possibility of a disastrous inrush of water into mine workings from over- and underlying water-bearing beds conditioned by rock disintegration, changes in mine pressure or weakening of the rock due to oxidation;

b) taking due precautionary measures when workings approach surface sources of water, abandoned mines and zones of tectonic disturbances;

c) utilization of mine water as a source of a water supply;

d) anticipating possible changes in chemical composition of underground water with respect to its aggressive action on mine equipment.

The role played by underground water in the formation and destruction of mineral deposits is of special importance.

One of the principal tasks in this field is to ascertain signs of hydrogeochemical action during exploration of mineral deposits. This requires a study of altering chemical composition of underground waters, particularly of fluctuations in the content of various ore-forming elements.

Such a study of the regime of underground waters should be closely allied with questions concerning the effectiveness of measures taken against these waters at the mine.

Other first-hand problems are: behaviour of the rock in the mine, distribution and development of mine pressure, and stability of country rock in relation to natural and artificial factors.

It should be noted incidentally that engineering geology and special experimental work pertaining to rock stability are not yet receiving the attention they deserve in mining.

A systematic study of these problems may be conducted only with the aid of special hydrogeological stations which should by no means limit their activities to current practical mining needs, but also bend their efforts to the solution of theoretical questions of hydrogeology and engineering geology. Such stations must properly choose and technically assimilate their territories.

B) NATURALISTIC FACTORS INFLUENCING WATER ABUNDANCE OF MINERAL DEPOSITS AND THE REGIME OF UNDERGROUND WATERS

The rich variety of naturalistic forces in different regions predetermine the great diversity of hydrogeological environment of mineral resources.

Major factors influencing the water abundance of mineral deposits and the regime of mine waters are: climate, orohydrography, geomorphology, geology, tectonic pattern of a region, and mining methods. Recharge, the number and thickness of water-bearing strata, circulation, underflow, chemical composition, water abundance and the regime of mine waters are all dependent upon different combinations and the relative importance of the above factors.

Thus, the volume of water pumped during exploitation of deposits occurring under similar conditions but situated in different climatic regions will depend upon the amount of precipitation.

For deposits lying in regions of permafrost, recharge is greatly hampered.

Hydrogeological conditions and the regime of underground waters of deposits occurring in karst districts are in a great measure subordinate to the climatic zone of the given area. In southern regions where precipitation predominantly takes the form of heavy rainfall and where there are no cover formations, open karst is the rule. In these latter regions, if other conditions are equal, the regime of cavern (karst) waters will be directly related to the quantity and character of precipitation. Water abundance of mineral deposits in arid zones is generally much less than in wet climes.

Orohydrographic and geomorphologic factors are quite often of decisive importance in the occurrence and regime of underground waters, where depth and pressure head of which largely depend upon the hypsometric position of intake areas of the aquifer and the depth of the arterial drainage system.

It is evident that if the floor of the mineral stratum lies above the local erosion base the flooding of the deposit will be insignificant, and conversely, if it lies below the base there will be a more or less water-invaded deposit.

In the latter case the abundance and regime of mine waters will be greatly affected by the location of the deposit or of the particular section of the mine. For example, the water regime of a mine section located on a divide may quite differ from one situated close to a surface stream or basin.

The tectonic pattern of the region is no less important: deposits occurring in large synclines have a greater water saturation and the regime of mine waters is more stable there than in places with small geostructures or complicated structural geology generally. Deposits in permafrost regions are marked by a variety of hydrogeological and geological features, giving rise to a number of specific problems connected with the survey of mine waters there.

Finally, the sum of mining methods exercises a considerable influence over the water-bearing horizons occurring in roofs and floors of mineral deposits.

Drainage of water-bearing strata begins with shaft sinking, is intensified during development stages and reaches its maximum with stoping. In the latter operation the disturbance of overlying rock continuity and consequent changes of correlation between water-bearing strata (and under certain conditions between such strata and upper bodies of water) is contingent upon the mining methods adopted.

C) DATA REQUIRED FOR THE SELECTION OF A SITE FOR THE STATION

Adequate organization and assimilation of regime observations are feasible only with a proper knowledge of the general geology and hydrogeology of the mine area and

only after a detailed study of the mine section (either exploited or planned) has been completed. Available information frequently proves insufficient and must be supplemented by additional hydrogeological investigations, beginning with a general survey of the area and terminating with a detailed survey of some particular section of the mine.

Not touching upon surveying methods, we shall only note the general purpose of the detailed hydrogeological survey, either of a planned or already exploited field.

In taking such a survey, attention should be chiefly directed toward the clarification of factors either hindering or facilitating the infiltration of surface and atmospheric waters and the disposal of mine waters.

The survey must reveal the places where sands or limestones are found under a thin cover of impervious rock, as well as areas marked by artificial disturbances of the ground (hollows, ditches, pits, quarries, funnels from abandoned workings, and cracks and settlements due to caving of long walls and influx of quicksand). A most consequential role during intensified flooding and breaking through of surface waters is played by karst and tectonic disturbances, as well as by ponds, marshes and gulches. Abandoned mines also do their part.

In the process of mining operations such a map of surface conditions must be periodically supplemented by new data.

After due investigation and digesting of all information obtained, including facts from practical sources, the following material should be prepared for the systematic study of the mine water regime:

a) plans of the station terrain drawn to scales of from 1:25,000 to 1:50,000, and of the area under study to scales of from 1:5,000 to 1:10,000 with delineations of all geological, hydrogeological and permafrost data;

b) geologo-lithological and permafrost ground profiles (cross-sections); these should contain bore logs embraced by the profiles, water levels of all aquifers, geothermal data, thickness and zone of the active layer of eternally frozen ground and other specific information regarding the given area;

c) a map showing lithological composition, and with isopachyte and hypsometric lines of the impervious rock (preferably for each individual aquifer);

d) a map delineating lithological composition and isopachytes of the rock comprising the bottom of the mineral stratum with simultaneously plotted hypsometric lines;

e) the same for the roof of the mineral stratum;

f) contour maps of the water table, including isohypsometric lines of the impervious bed (preferable for each individual aquifer);

g) combined maps of water table contours and hypsometric lines, separately for the roof and bottom of the mineral stratum;

h) maps charting the values of hydrostatic heads acting against the roof and bottom of the mineral stratum;

i) maps illustrating the hydrochemical composition of mine waters;

j) geologo-lithological cross sections (profiles) as well as boring logs of wells and other workings, showing: water-well construction, levels of all aquifers, numerals of laboratory analyses at corresponding depths, percentage of core recovery, rate of drilling, fluctuations in water level, as well as the condition of the drilling fluid and pipe casing in the process of boring;

k) schedules of stationary observations of the regime of underground waters and surface streams and basins;

l) graphic material on pumping tests and water injections (cross-sections, depression curves, diagrams of the relation between discharge and drawdown, computations of the coefficient of filtration, etc.);

m) tables and information derived from field and laboratory work (tables summing the results of pumping tests and injections, determination of mechanical, chemical and thermal properties of the rock, information relative to mine operation, open pits, etc.).

The boundaries of the territory covered by the hydrogeological station are subsequently determined by properly coordinating all the above data.

D) GUIDING PRINCIPLES IN LOCATION OF OBSERVATION POSTS ON THE STATION SITE

Siting of wells and other observation points should be commenced upon the termination of preliminary work and after the limits of the territory to be covered have been defined.

In order to trace the entire regime of underground water, beginning with its incipient state, all posts should be set up prior to commencement of mining operations.

Certain difficulties present themselves in the preparation of systematic instructions relative to distribution of the observation network. This is due to varied natural circumstances and combinations of factors affecting regime changes of mine waters. Therefore, our discussion of such a distribution of posts and the principles for the study of the regime is based on examples of deposits with the most complex flooding conditions, classified into the following groups:

Group I—deposits occurring principally in loose sandy and clayey rock, such as in the Moscow coal basin and the Ukrainian deposits of lignites;

Group II—deposits found in complex hard or medium-hard fissured rock (Donets, Kuznetsk and Chelyabinsk basins);

Group III—deposits lying in carbonate karsts (Kizel coal basin and Baltic basin of combustible shist);

Group IV—deposits occurring under conditions of permafrost.

Group I. Deposits Occurring Principally in Loose Sand or Clayey Rock

The cross-section shown in Fig. 24 is an example of complex hydrogeological occurrences for this group.

Its main features are high water content and elaborate hydrogeological and geological conditions.

Both the Quaternary and the primary Paleozoic sediments are highly watered. The most important factors to be considered in the mining of this deposit is the water-

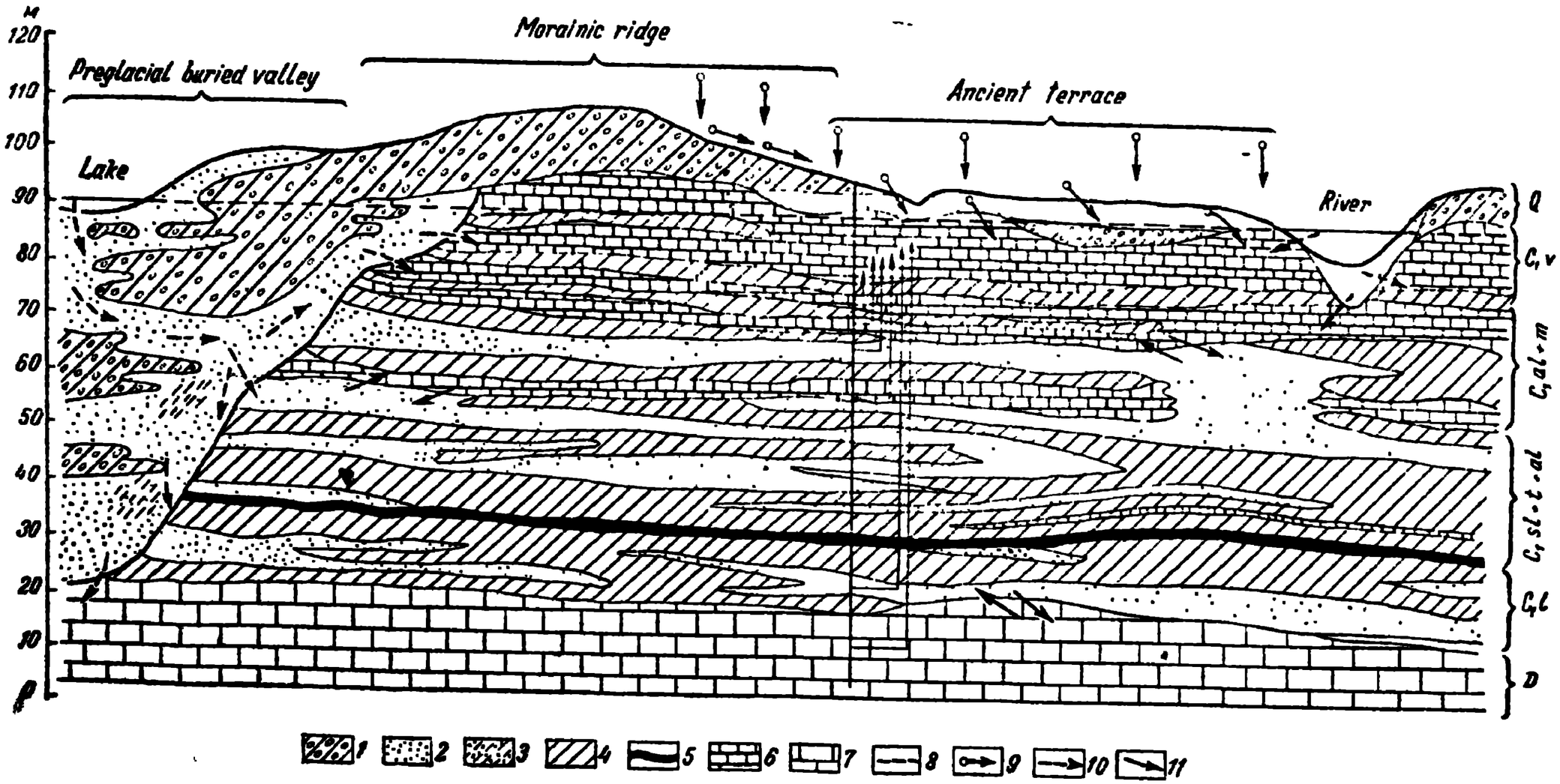

Fig. 21. Hydrogeological cross-section of a coal deposit (according to L. P. Nelyubov).

1—moraine sediments; *2*—various grain-size sands; *3*—silt-clay sands; *4*—various types of clay; *5*—coal seam; *6*—limestone; *7*—limestone and dolomite; *8*—static water level of the Venevian series; *9*—main water routes for recharge of the Venevian limestone aquifer; *10*—scheme of hydraulic communications between the bedrock aquifer and surface waters; *11*—scheme of hydraulic communications between bedrock aquifers.

bearing capacity of the Quaternary sediments filling the preglacial depression, which represents a huge collector and reservoir containing considerable quantities of underground waters.

Except for the upper water-bearing stratum of Venevian limestone, an alternation of saturated and impervious rock in the Prequaternary formations predetermines the existence of a number of aquifers of considerable pressure head.

The stratum of Venevian limestone is particularly charged with water due to its fissured and cavernous nature, and when exposed at the river or lake edge is in the closest contact with aboveground sources.

Because all water-bearing strata are bisected by a deep depression they are hydraulically linked, which is proven by their uniform level. Still, during mining operations their influence on mine flooding will differ in individual areas, depending upon the distance of the workings from surface streams and from the preglacial depression, upon the effectiveness of the seal between separate water-bearing formations and their distance from the coal seam. Hence when preparing to sink a network of observation wells, these facts should be given basic consideration.

The first thing to be taken into account in distributing the wells is the significance of each water-bearing formation in mine flooding. In the above example, the greatest roles will be played by high-pressure waters under the coal seam, as well as by the aquifers closest and overlying the roof. The uppermost saturated strata in the limestones may exert a certain influence over intensified flooding, in accordance with the degree to which the continuity of the rock underlying the limestone is disturbed during caving of longwalls.

The regime of underground waters and the rate of flow into the mine will be affected by the state of aquifer recharge. Thus Fig. 24 shows that although the waters of the preglacial depression are most actively connected along a wide front with the lower aquifers, their link is considerably smaller with the upper ones; however, these latter are closely associated with the river.

When sinking observation wells, account should be taken

of large features of underground topography as well as structural disturbances. The latter present a danger of flooding the mine and may exert an influence both upon changes in regime as well as on the interrelation between water-bearing formations during mine operation.

To follow the development of a depression cone when the mine area is to be widened, bores should be provided for not only in the mine terrain but also beyond its boundaries where the regime of underground waters has not been influenced by mining operations. Wells sunk within the limits of the colliery permit tracing the character of disturbances in rock continuity in order to prevent flooding intensification or water influx into stoping areas following caving of longwalls.

Observations are to be conducted not only in specially drilled bores, but also in natural springs, wells and catchments whose connection with the given aquifers is beyond all doubt. There is no need to add that parallel observations of the regime of surface streams and basins should be conducted with the aid of water-gauge stations (and spillways—for small streams).

Group II. Deposits in a Hard or Medium-Hard Fissured Non-Cavernous Complex of Rock

This group includes coal deposits in the Donets, Kuznetsk, Karaganda and Ural basins and certain lode deposits.

The above coal deposits occur in interlayers of sandstone, shist, siltstone, argillite and sometimes in bands of limestone. This rock is frequently variously folded and complicated by a whole system of large and small structural disturbances dividing the deposit into a number of sections of different size.

Depending upon the facies of the rock, the productive series contain several variously connected aquifers chiefly enclosed within fissured sandstone, siltstone and limestone. The impervious rock is represented by sand-clay and clay slates, as well as argillites.

In large areas the productive series are overlain by a

thin layer of Quaternary loams, and the quantity and regime of their mine waters are subordinate to a number of natural and artificial factors, the principal of which are:

a) terrain topography;

b) lithological composition of the rock and its strike, and the distance of the mine from constant aboveground streams;

c) structural geology;

d) the area and depth of the mine;

e) the presence of old flooded workings in the mined area or in its proximity.

If there is a smooth upper relief the water abundance of the rock will usually be low, but will rise sharply if the mine field is cut by, or adjacent to, a river valley or repeatedly intersected by gulches and ravines. In the latter case the possibility of the penetration of surface waters into mine workings will greatly increase.

The strike of the rock to permanent flows and the latter's distance from the mine is very important. Saturation of the deposit increases when the rock strikes across a surface stream, since this facilitates recharge of the water-bearing strata.

Water saturation of the above group of deposits is subservient to rock dislocation as well as to the existence and nature of large structural fissures, filled (or not) with secondary formations. The latter often limit the intake areas of the aquifers, and sooner or later the flow into the mine will not only show no increase, but will actually decline due to depletion of static sources. The inflow may be high but stable if flooding is effected with the active participation of surface streams affiliated with the workings through structural fissures not filled with secondary formations; or may even rise when surface waters penetrate into workings through cracks caused by caving.

The listed factor should be carefully considered when choosing observation sites for the given types of deposits. Due consideration should always be allowed the lithological character of the rock and the structural geology of the area. When surface streams are present, observation posts should be allocated along transverse lines running from the area under investigation towards the river valley.

Deposits in graben depressions occurring in solid masses of limestone, shist, or igneous rock are very often met with. The productive water-bearing series filling the deep trough consist of sandstone, conglomerate, argillite, and silt rock. These formations are folded and often complicated by disjunctive disturbances. In some regions both the productive sediments and the older ones enclosing them are in their turn transgressively covered by water-bearing sands or silicic marls distinguished by their high saturation. Roof caving over mined areas engenders intensified or even sudden influx of water from sands or silicic marls into the workings. Here the purpose of regime observations is to find the intake areas of underground waters. Depending upon geological and structural features, bores should be sunk along transverse lines embracing the entire catchment area of the depression, with a concentration of posts in crushed zones of structural contact and in the vicinity of rivers.

The occurrence and circulation of underground waters in the rock belonging to the magmatic and metamorphic complex are especially peculiar. Intersected by numerous dikes and complicated by a system of structural disturbances, the latter contain an abundance of crevice water, while the rock enclosing ore lodes is of low water capacity. All this demands that the majority of observation wells be driven at the crossings of several water-bearing dikes or zones of structural disturbances, as well as in the vicinity of surface streams and basins.

Group III. Deposits in Carbonate (Cavernous) Karsts

Deposits whose high-water content is associated with cavernous (karst) limestone and dolomite are very numerous.

The general extent to which the hydrogeology of the region has been investigated will be of prime importance in the study of such deposits, whether for purposes of mining or otherwise. Observation points should be introduced while the general hydrogeologic survey is in progress, with sub-

sequent expansion and correction of the network in the course of detailed exploration.

The methods already noted concerning distribution of observation posts will be fully applicable to this third

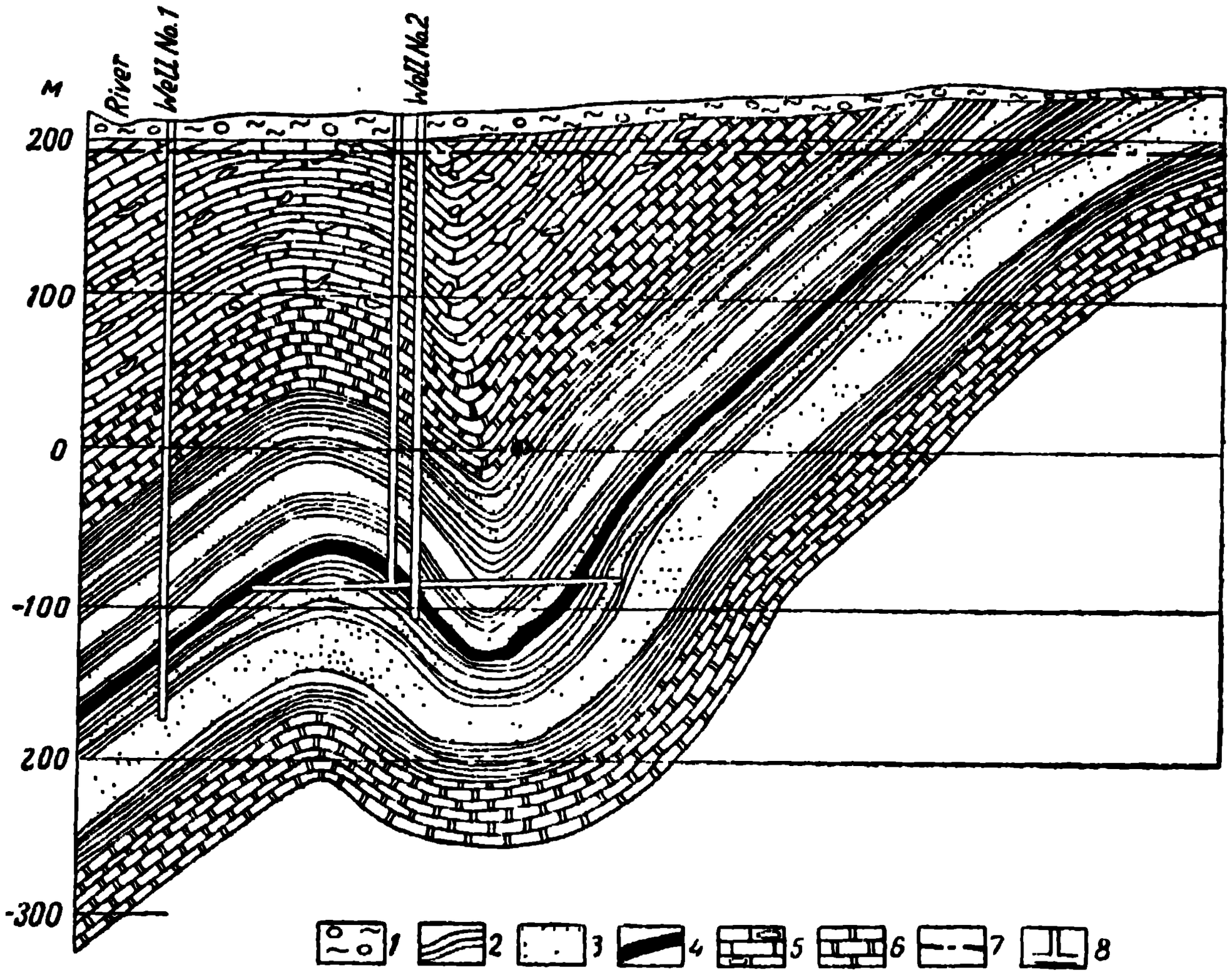

Fig. 25. Hydrogeological cross-section of a mineral deposit.

1—overburden; *2*—clay slate; *3*—sandstone; *4*—coal seam; 5—limestone of high cavernosity; *6*—limestone of low cavernosity; *7*—level of ground water; *8*—mine workings.

group and we shall therefore dwell only upon certain additional features.

In karst regions the objects of principal study should be the interrelation of cavern and surface waters as well as of other water-bearing strata possessing few or no caverns; investigations should also include conditions of water occurrence and recharge, and vertical and lateral circulation. Some other very important points are the river regime, surface run-off, and the total water inventory of the area. Bores should be concentrated at sink holes, in dry valleys

indicating possible underground flow, in zones of structural disturbance and at steep dippings of mineral layers (Fig. 25). A sharp eye should also be kept for areas where test bores have exposed considerable absorption of the drilling fluid. Other important points to be noted are: places showing intensive absorption and outflow of surface waters; the amount of water absorbed or released in any section of the area. The velocity, regime and direction of underground flow in dry valleys in the vicinity of, or above, mine workings should be studied to prevent a sudden inrush of such waters into sections where the roof has caved.

We are emphasizing the above for the following reasons. Where deep caverns exist a shifting of the rock will cause sharp hydrogeological changes in the underground water regime, form new routes for the circulation of cavern waters, and transform passive karst zones into active and water-free rock into water-bearing. This may cause an increase, or a catastrophic burst, of cavern waters into the mine, at times reaching hundreds of cubic metres an hour. Here water inflow dynamics is largely dependent not only on the nature of the rock but on mining methods, for the latter will determine the intensity of fissure and crack development.

It follows from the above that observation wells should be sunk not only into cavernous and structurally disturbed limestone, but also into cavern-free rock of regular occurrence not in contact with the mineral deposits. Where large disturbed structure is encountered, observation wells should be sounded on either side, i.e., both into the up- and down-thrown rock.

In the deposit illustrated in Fig. 26 the principal mine inflow types are associated with aquifers enclosed within fissured and cavernous limestone. The latter is pinched between igneous and metamorphic rock with very low permeability and forms a sumptuous reservoir of fissure and cavern waters. Survey bores in such regions should run along lines perpendicular to each other so as to follow and cross the underground stream, and should reach to above-ground basins and streams with the purpose of exposing their influence upon underground water replenishment during the mining of a deposit.

We have already pointed out the importance of the study of river regimes when dealing with cavernous structure.

Hydrometric stations should be located above and below cavernous rock outcrops characterized by such karst phenomena as sink holes, etc. This demands consideration of geological and hydrogeological features of the area; many river valleys cross the strike of rock of various age and lithological composition, resulting in varied degrees of cavern formation and water flow along the course of the river. For this reason hydrometric stations should embrace differing stratigraphic horizons or varied lithological rock composition. Subsequent conclusions concerning the recharge of water-bearing formations by surface sources and the degree of influence exercised by various aquifers over the flooding of mine workings may be drawn on the basis of hydrogeological observations and the elevation of one or another of the cavernous beds in relation to the mineral stratum.

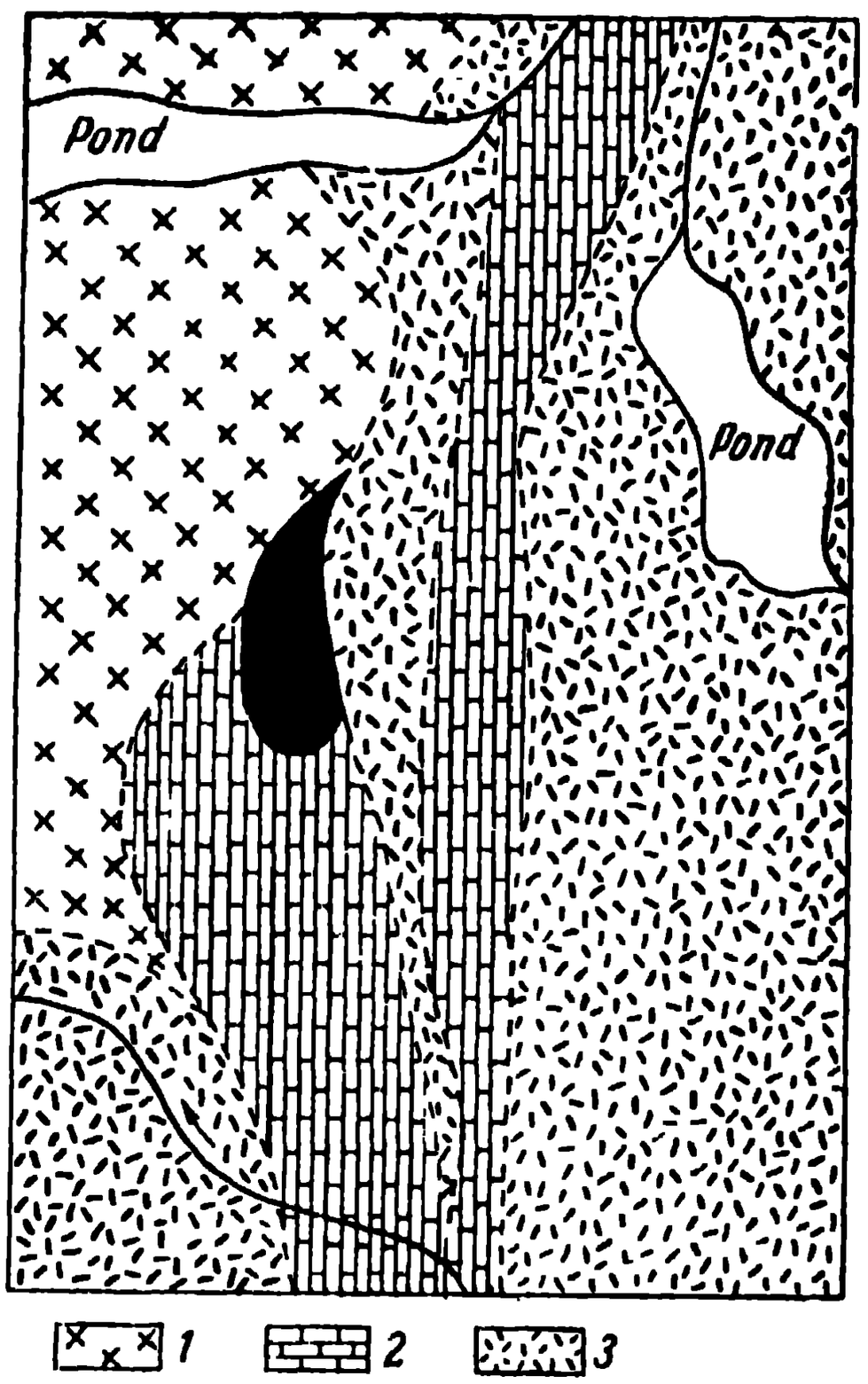

Fig. 26. Geological map of a mineral deposit.

1—syenite, syenite-porphyrite; *2*—limestone, *3*—porphyrite and tuff; *4*—outcrops of mineral deposit.

Group IV. Deposits Occurring Under Conditions of Permafrost

The regime of underground waters in deposits where the forces of permafrost prevail has its own specific peculiarities. Consequently, together with general hydrogeological problems, a particular inquiry must be made into the ther-

mal regime of the rock, surface and subsurface waters, and their chemical and mineral composition.

A distinctive hydrogeological feature in regions of permafrost is the appearance of taliks of various size in the solid mass of frozen ground. These taliks create an extremely interesting interrelation between the waters occurring above, within and below the frozen ground, as well as between these three and surface streams and basins. This should be taken account of during location of observation posts.

A second important consideration, especially in mine construction and operation, is the ability of constant streams of underground and surface waters to defrost the frozen ground, gradually increase the water inflow, and threaten the mine with flooding. With the melting of ice in loose rock during exploitation of a mine, the formation of quicksands is possible with a resultant change in side pressure. This may deform the mine workings and cause intensified inflow or a sudden influx of surface waters.

Complications of considerable magnitude may appear in deposits occurring near the sea. Sea water freezes at approximately —2°C. But because freezing causes an increase in mineralization, sea water may percolate into the rock at even lower temperatures. We know that with heightened mineralization the freezing point of water drops, and that with a maximum salt saturation it freezes only at a temperature of —22°C. Therefore, it should be borne in mind that in probing frozen ground containing readily soluble halides, a highly mineralized water may be found retaining its liquid state. Sea water can freely penetrate into mine workings through crevices and voids filled with ice, particularly when zones of structural disturbances reach the shore.

Observation points should cut across river valleys, the shores of lakes or seas as well as across and along the strike of water-bearing strata. Bore sinking operations should also take account of terrain topography, taliks, depth to the permafrozen horizon, and outflow both between and below layers of the frozen ground. Particular notice should be directed to zones of large structural disturbances, to the composition of loose series of rock, and to the presence of ice in the latter or in the voids of cavernous rock.

Mine terrain not yet being exploited but which may undergo temperature changes and changes in water mineralization due to pumping operations, caving of roof, and warming by incoming water and air is absolutely subject to observation borings.

E) SURVEYS IN MINES

Observations of the regime of mine waters may be commenced only after a detailed geological and hydrogeological survey has been taken, both of the region and the local mine area, and only after all information thus obtained has been properly analyzed.

The results of such surveys should insure the possibility of anticipating any hydrogeological or geologo-engineering situation that may arise during mine expansion. Investigations should include:

1) underground hydrogeology;
2) mine water inflow;
3) level, temperature and chemical properties of underground waters;
4) rock stability of the roof and floor of the deposits.

Problems pertaining to mine waters are dealt with in part in the following manuals and regulations: A. S. Sergeyev and D. D. Belyaev (1936), V. M. Ponomarev (1937, 1938), S. V. Troyansky and D. D. Belyaev (1938), D. D. Belyaev and A. A. Vorobyev (1940), S. P. Prokhorov (1939, 1951).

1) The Underground Hydrogeological Survey

An underground survey plays a big part in the study of mine water regimes, in the proper organization of mining operations, and in planning of drainage and pumping both from individual water-bearing stratum and from separate galleries and greater tracts of the mine area.

During preliminary examinations prior to the selection of observation points, it will be necessary to make a detailed study of the entire mine drainage system and to plot on the mine survey all pumps, mains, sumps, seals,

drainage ditches and other installations such as stemmed filters in the floor and the roof of the seam, through-filters, drainage channels and wells.

Then should follow a detailed hydrogeological survey of the whole mine, the aim of which (and of no small importance) is the selection of typical observation points.

This survey, which should be accompanied by plans and sketches of flooded areas (drawings which are to be systematically supplemented during normal mine exploitation), should embrace a description of the mineral stratum (hypsometric characteristics, faults, sinks, squeezes, crushings, washouts, etc.), of lithologic composition of the rock in the roof and floor of the workings, facies, physical and mechanical properties of the rock, and of "sand windows" in the roof and floor of the stratum.

All water-bearing formations encountered during the sinking of shafts and driving of crosscuts, adits, raises, etc., should invariably be taken note of. If the mine has several operating levels, the lithologic composition, thickness, pressure-head in the water-bearing strata, and water-yielding capacities of each individual bed should be noted.

Structural disturbances are to be plotted and properly coordinated on the maps of flooded areas. Caverns, voids, fractures of tectonic origin, the predominant fissure system and its orientation, and the approximate fissure coefficient should all be shown.

Studies of caverns and structural disturbances should include lithological composition and the nature of their secondary formation fill.

Furthermore, the plan of the flooded areas should display deformations of the bottom and roof of workings and condition of timbering (props), should indicate the sections with elevated pressure, timber failures, heavings, and reduced cross-section of the workings and show the locations of underground water influx either from the floor or roof.

Untamped prospect bores often result in a direct communication between aquifers and an intensification of inflow or flooding by underground waters. Therefore, note

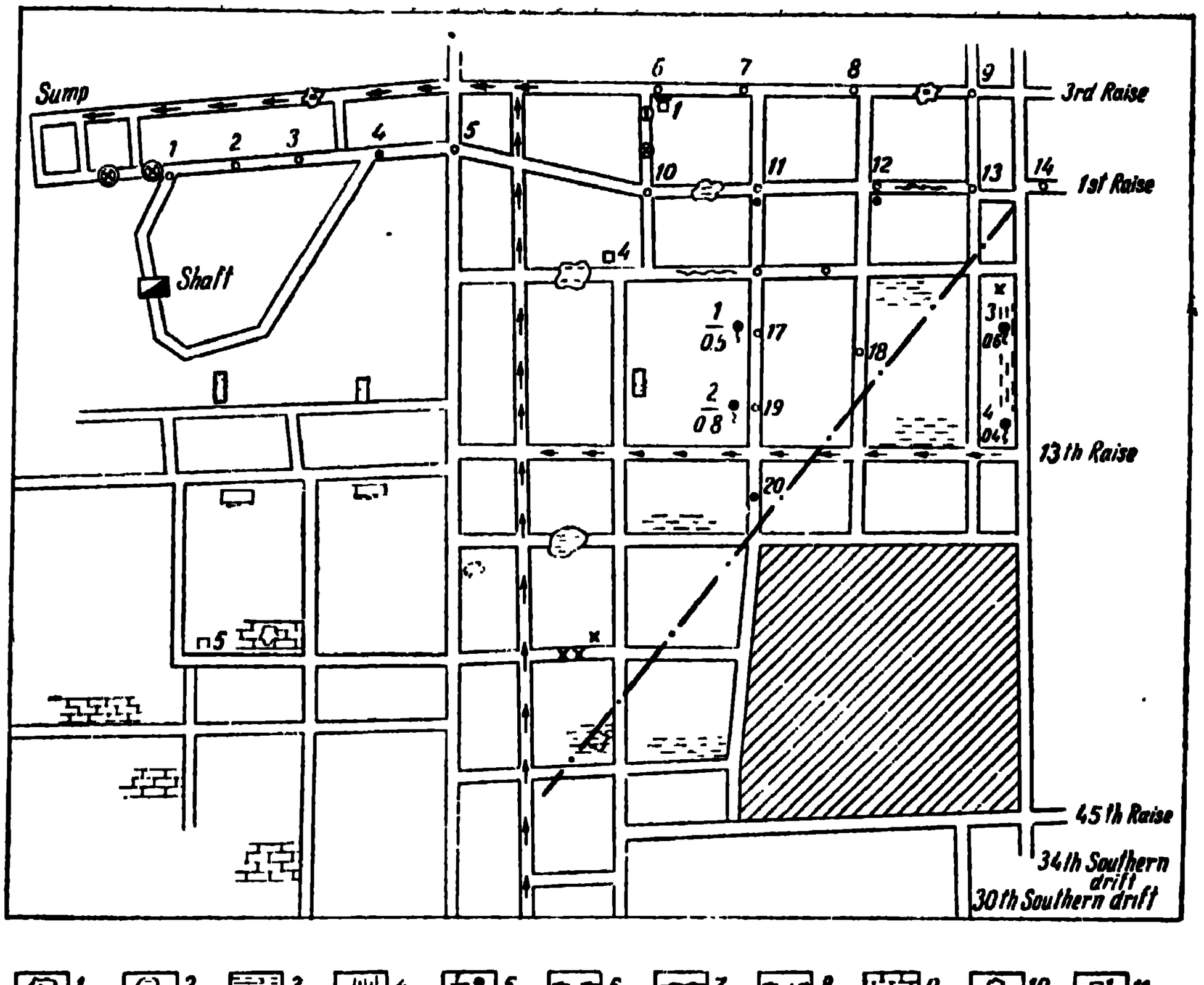

Fig. 27. Schematic plan of mine workings.

1—water inrush from roof; *2*—water inrush from bottom; *3*—water from bottom; *4*—roof water (drip); *5*—springs and their discharge in litres per second (numerators are the numbers of springs); *6*—direction of pipe mine drainage flow; *7*—heaved floor; *8*—direction of gravity flow of mine drainage; *9*—outcrops of limestone in bottom; *10*—cavernous rock; *11*—enumerated drainage wells; *12*—enumerated stemmed filters in roof; *13*—enumerated boreholes in bottom; *14*—mine pumps with a capacity of 100 m³/hour; *15*—mine pumps with a capacity of 50 m³ hour; *16*—mine pumps with a capacity of 30 m³ hour; *17*—mined out areas; *18*—line of structural disturbance; *19*—timbering failure; *20*—sand patches in bottom; *21*—sand patches in roof.

should be made of the situation of wells in the proximity of the mine, as well as of all divergences discovered in the description of rock, based on prospecting data.

Material acquired by the survey should be delineated as shown in Fig. 27.

2) Observation of Mine Water Inflow

All mine workings and shafts should be closely watched for water inflow.

Inflow should be gauged by means of filters from the roof, floor, walls, special wells, blind shafts, cross-holes, and other workings. Yields from discharge wells sunk from aboveground should be recorded separately.

The character of the flux should be noted on the plan of flooded sections, as for example: jets, dripping, springs, fountains, wet places, as well as the duration of all these occurrences.

Particular pains should be taken as regards inflow from surface bodies of water, seasonal influx of spring high floods, heavy rainfall, etc., as well as sudden inrushes from water-bearing formations and old abandoned pits.

In the latter case—a sudden charge of waters—note should be made of its causes, source and duration, intensity and character, the volume of washed out sand, disturbances in the surrounding rock, changes in flooded neighbouring workings, and the effect of the influx upon the overhead terrain.

In studying the flow from old workings it is necessary to indicate the type of opening connecting the operating (new) shaft with the old, and the method employed in regulating the flow. Should water be diverted by special discharge pipes through a pillar, its yield and head should be indicated.

When mining beneath surface streams or other bodies of water, the depth below the river bed or bottom of the basin should be noted, as well as the geological cross-section of the rock from the roof to the bottom of surface waters, the character of rock settlement in the roof and the method employed for caving the roof, the time required for water from surface streams to reach the workings after longwall caving, and the character and dynamics of the inflow.

When water proceeds from the stope, the amount of inflow, the area mined, and the extent of roof caving should be determined.

There are various ways of gauging inflow. If the flow is in the form of dispersed dripping it should be collected on

iron sheets placed close to the roof. Sheets should be suspended to provide a concentrated run (at one point) which is then gauged with the aid of a measuring vessel.

If the drip is relatively uniform, small vessels are employed with an area of 1 m^2, made in the form of deep trays with handles provided below. Measurements are carried out at several representative points and the average result thus obtained for 1 m^2 of the roof is then extended to the entire given roof area. If this method is not practical, drip should be gauged by measuring the difference between the discharge at the drainage ditch before and during the flow.

Repeated drip measurements should be conducted at the same points on dates dictated by local conditions and at intervals of 5-10 days or longer. Factors which have influenced the intensity of inflow at any point should not be lost sight of, including the factors in neighbouring workings, such as influx from the floor or roof, drainage of water-bearing strata by neighbouring areas, driven filters, through-filters, etc.

Water inflow from the floor should be collected by a trough in case of dispersed influx, while spurting sources should be measured with the aid of short iron pipes driven into the soft ground, the space about each pipe being tamped with clay or cement. Pipes may be provided with offsets which will make it easy to measure the discharge by means of a measuring vessel.

For large discharges, trenches and spillways should be constructed.

Influx from the drift face and the adjacent area is gauged summarily, the water being collected in small ditches and then conveyed to the main sump. Large inflows are conducted to a well which is then pumped out.

Recordings accompanied by sketches should also be made of inflow from the floor and roof, state of fissure, the crush structure of deposits and their enclosing rock, of structural divergences, etc.

Another major point is the recording of the total amount of water pumped from the shaft; this gives an understanding of the degree of flooding of the given section. The total flow into the mine should be equal, within limits of

possible accuracy, to the sum of flow from individual stopes and other sections.

Total inflow may be determined in the following manner:

a) by the capacity of pumping plants; the capacity of each pump should be exactly established. Control tests of pumps should be conducted during definite lengths of time, such as in the course of one shift, the characteristics of the pumps being noted in the mine journal, including nominal and actual capacity, and time of operation and stoppages;

b) by readings of the water gauge installed on the pressure line of the pump;

c) by pumping of water from the main sump;

d) by recording the time needed for the water in the sump to recover its level after it has been evacuated;

e) by an aboveground installation consisting of a box and spillway; if the yield from the shaft is small (up to 50 m^3/hr.) the spillway may be substituted by a measuring box (or barrel) with a volume of up to 1 m^3, in the bottom of which a hole is provided for the outlet of water after measurements are taken.

Indicative of the flooding of a mine is the water-yielding coefficient (the volume of water in cubic metres per ton of the ore hoisted), which may vary for one and the same mine at different seasons of the year.

3) Level, Temperature and Chemical Properties of Underground Waters

A complete cycle of level, temperature and chemical control of underground waters is conducted:

a) when water-bearing horizons are all intersected by the mine;

b) when one and the same water-bearing stratum is intersected at different horizons;

c) in areas of typical structural elements (troughs, anticlines, flexure bends, structural disturbances) and karst phenomena;

d) in zones of sharp lithological changes in the roof and floor of the mineral stratum, in areas of structural variations within the mineral stratum itself, and along contact lines of different types of rock;

e) in areas of water influx from the rock composing the roof or bottom of the mineral stratum;

f) within the stoping area and in the zone of roof settling development;

g) when galleries approach surface streams and basins, zones of large structural disturbances and old workings;

h) in areas of heavy flow of underground waters into the mine;

i) in all active drainage galleries; here, besides level, discharge and chemical observations, studies must be conducted relative to character, amount and changes in sand washout;

j) in zones of overloaded props and floor heavings.

When recording the temperature of rock in a mine situated in permafrost territory the thermometer in the drill-hole should be thoroughly insulated to protect it from the influence of the air. Since it is difficult to do this in fissure rock, the holes should be drilled in solid sections of the walls.

Apart from the study of the thermal regime in the active and productive layers, physical and mechanical properties of the rock should also be determined by laboratory test (granulometric composition of the skeleton of the frozen ground, ice formation, ice content, volume weight of the natural structure, and specific weight of the solid matter). Furthermore, qualitative determinations should be conducted to characterize the physical condition of the rock (thawing, desintegration through soaking and effervescent test).

4) Observations of Rock Stability in the Roof and Floor of Workings

Important criteria in the study of the regime of mine waters are: deformation of timbering (props), shifting of rock during the caving of longwalls, floor heaving, falling in of rock, etc.

The intensity of shifting will be due largely to mining and propping methods, length of longwalls, and methods employed in forced caving of the roof. The problem of roof and bottom stability of the mineral stratum is very complex and becomes particularly so when deposits occur in

series of sandy and clayey rock. Therefore, our concluding remarks are applicable, in the main, to this particular group of deposits.

The question of roof and bottom stability generally embraces:

a) physical and mechanical properties of the rock comprising the roof and floor of the mineral stratum; hydrogeological conditions and hydrostatic head; the behaviour of the roof and floor (heavings, falling-in, bulging);

b) changes in physical and chemical properties of mine waters during exploitation of the deposit. This is important in preventing fall-ins and roof caving;

c) methods of forced roof caving, their duration and the character of the subsidence of the aboveground surface.

In studying pressure development in the roof, recordings should embrace settling or bulging, the appearance and development of fissures, their orientation and water content, the commencement and development of water drip or concentrated flow, falling of pieces of rock, and the character of propping deformation. In permafrost regions such investigations should include the composition of the loose mass of the rock which often contains lenses of ice.

The duration of settlement of roofs composed of solid rock is measured in months and even years. The process is faster when the roof is of sandy, clayey or medium-hard rock. The contour, depth and general dimensions of the settling area will vary according to a number of factors. Thus, filling of stoped areas reduces the zone of subsidence. In a sharply dipping seam this subsidence assumes the form of a narrow, deep hollow with steep walls. Subsidence of the upper terrain and in the mine itself should be properly described and sketched and then plotted on the plans.

Upswells accompanied by propping failure sometimes appear in the floors. In analyzing such occurrences, recordings should be made of the date of their appearance after driving the drift, size of the deformed areas in the floor, moisture content of the rock, the existence of fissures, joints, etc.

Boring of trial wells is recommended for sounding the nature of the floor. Such wells should be thoroughly tamped when no longer needed.

CHAPTER III

METHODS OF FIELD WORK IN THE STUDY OF UNDERGROUND WATER REGIMES

1. THE COMPOUND NATURE OF THE STUDY

Field methods used in probing regimes of underground water during hydrogeological investigations have long been in the process of development.

All more or less extensive hydrogeological work involves the study of underground water regimes. Such studies, however, are too often confined to chronological observations of level fluctuation, while chemical and temperature variations are just as often ignored. As a result, the data obtained is inadequate and does not reveal the natural processes of an aquifer, for this single factor alone (level fluctuations) does not allow investigators to arrive at exhaustive conclusions nor to find flawless explanations of the phenomena. Hence they are in no position to offer well-founded forecasts of the regime of underground waters.

Chronological temperature and chemical fluctuations observed without consideration of level variations are likewise incomplete. But combined prolonged analyses of chemical as well as other factors of underground water regimes will disclose the laws governing the origin of the chemical composition of the latter.

A compound study of the underground water regime should include level, discharge, temperature, chemical composition, zones of aeration and the latter's relationship to free ground waters.

The fullest possible consideration should also be given to geology, meteorology, hydrology and soils of the given region. Furthermore, depending upon the general purpose of any hydrogeological station, the analysis should cover

soil solutions, microflora, gas composition of the water, etc. If divorced from all these factors the study will have neither theoretical nor practical value.

When analyzing the data obtained, all the above elements should be considered in their relation to each other.

Below we describe observation methods of individual elements of the regime of underground waters.

2. EQUIPMENT OF OBSERVATION POINTS

Observation points for the study of the regime of underground water should consist of boreholes and springs. Neither pits nor dug wells are recommended for the purpose, since their utilization would result in a great distortion of natural factors.

The comprehensive nature of the study demands that observation points be equipped to enable them to carry out all necessary measurements of water levels, discharge, temperatures and sampling of water for chemical analysis.

A) BOREHOLES

Drilling should be done by generally accepted prospecting methods, particular care being taken not to miss any water-bearing formations and to protect the latter against clay pollution.

Types of accepted equipment have been described in detail by N. I. Kulichikhin in 1938.

Wells are usually cased with metal pipe of varying diameter, whose lower part should not be less than 100 mm. to ensure filter installation.

Filters are a very important part of the equipment and may be installed in two ways: the stuffing-box and the pipe column methods (Fig. 28), in both cases a settling chamber constituting the lower part of the filter. Particular care must be exercised in the proper selection of the filter's design. There are three well-known basic types of metal filters: screenless, screened and those with a layer of gravel. Proper selection depends upon the purpose of each borehole, conditions of underground water occurrence, the character

of water-bearing rock and the chemical and gas composition of the underground water. This latter determines the water's corrosive properties and its effect upon the materials used in the filters.

In regions where underground water contains a low pH value (acid waters), anti-corrosive filters made of wood, plastics or stainless steel must be used. Filters with screens of plastic material and glass fibre, recommended by V. M. Gavrilko in 1952, have found wide use recently.

In hard ground, observation holes should be fitted with a perforated steel casing, while in weathered ground they should be fixed by a non-perforated pipe running from the surface down to the bottom of the overburden and the weathered zone.

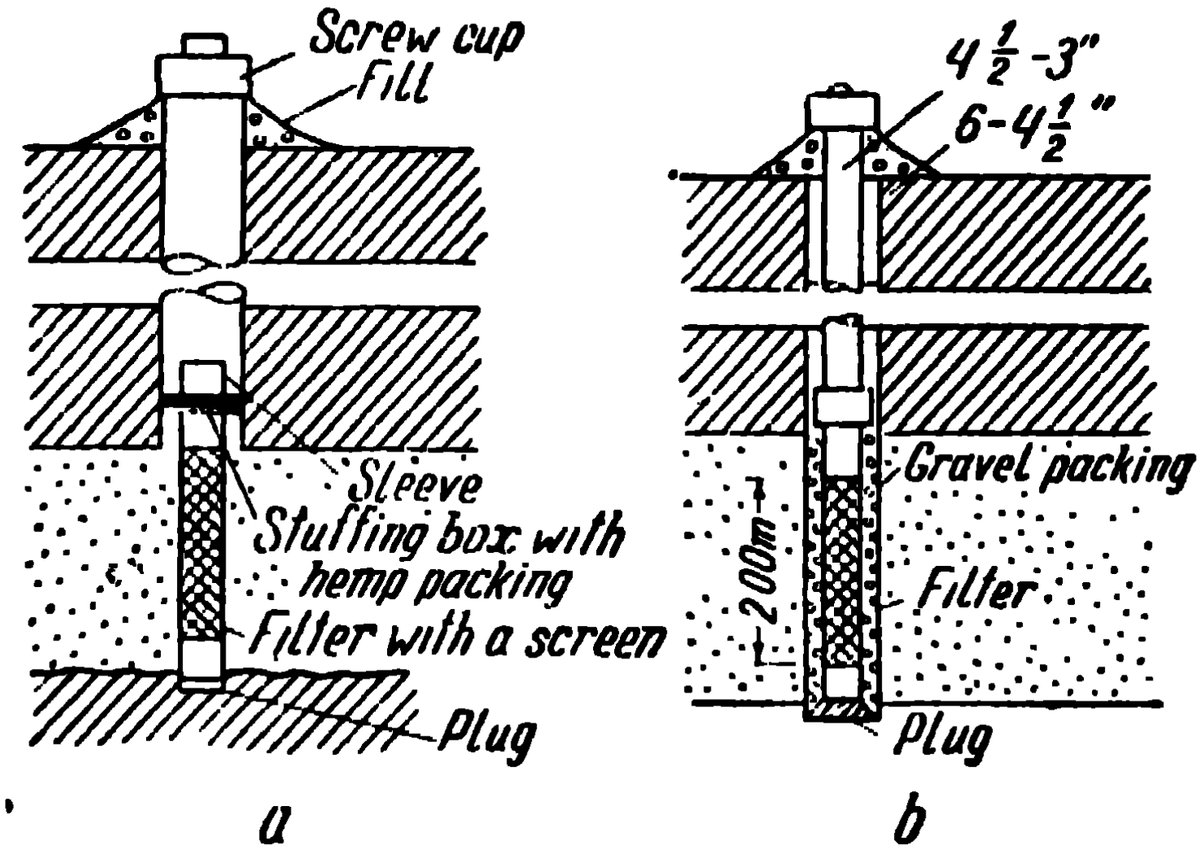

Fig. 28.
a—stuffing box filter; *b*—pipe column filter.

Where two or more formations occur, the casing string that seals off the upper aquifer should be left in place.

To prevent choking of wells, a special casing head should be provided.

In regions where pipes must be protected against frost, an insulated hut should be built over the bore or a felt cover provided for the pipe projecting above the ground. In southern regions where the pipe must be guarded against summer overheating, the casing head should be painted white.

Each observation point must be levelled and orientated to the benchmark.

Special boreholes serve the purpose of studying temperature fluctuations of free ground waters when these occur close to the surface. A perforated pipe made of an asbestos-cement compound and containing a gravel layer is sunk

into the water-bearing formation. At a depth of one or two metres from the surface (according to where the water table occurs) a steel pipe is either inserted into, or fitted over, the asbestos-compound pipe and fixed in place by means of clamps. At the surface the well mouth is concreted. The well must by all means be provided with a metal casing head.

Bores equipped for the study of ground waters in regions of peat bogs have their own special features. Due to the extremely small water yield of the peat, the wells used for this purpose should be of the smallest possible diameter, drilled with augers or disc-type drills, and without a subsequent lining. A more perfected type involves the employment of a rectangular pipe made of thick wooden planks lowered into the peat. Holes or longitudinal slots in the walls serve for the passage of the water. The pipe is lowered into a pit dug to the greatest possible depth, and then driven into the ground below the pit bottom, a pointed wooden end being first inserted into the pipe-end to protect it against being filled with peat. The boreholes may also be fitted with casings of perforated pipe with pointed steel tips for driving them into the ground. The upper end of the pipe should be either level with the surface of the bog or project above it about 0.5 m. After installation the pit is filled with peat and lightly tamped.

A pole mat should be provided around each borehole situated in a bog.

B) SPRINGS

All springs used for observations should be tapped by the simplest means and provided with a catchment arrangement that does not present any obstacles to measurements of discharge and temperature or to water sampling for chemical analyses. Catchments should be protected against washout or freezing.

Minor spring discharges should be measured by volumetric methods.

Trapezoidal or triangular spillways with permanent catchments should be installed on large springs.

The following rules should be observed in the building of a spillway: each spillway opening should have a suffi-

ciently sharp edge, and the water head gauged at a distance of not less than one or two metres away. To reduce the speed of flow in the upper side of the spillway, a settling tank with almost still water should be provided and periodically cleaned of silt accumulations. Another necessity is the access of air under the overflow of the weir; this is achieved by widening the bed below the wall of the spillway. The sill of the spillway should be levelled with the aid of a water level; the zero mark of the levelling rod for water-head readings should be on the same elevation as the sill.

3. EQUIPMENT AND INSTRUMENTS FOR THE STUDY OF THE REGIME OF UNDERGROUND WATERS

Instruments employed in the study of underground water regimes must comply with the following chief requirements:

1) sufficient accuracy;
2) simplicity in construction, convenience in handling or carrying from place to place;
3) temperature, moisture and corrosion resistance.

A description of instruments and equipment recommended for observations and collection of water samples is given below.

A) INSTRUMENTS FOR LEVEL GAUGING

Equipment chiefly encountered for levelling underground waters are level rods, tape reels, wire rope with plumbs of various design, and manometers and floats, including self-recording limnigraphs.

Water-stage gaugers may be either portable or stationary (permanently fixed to the observation point).

Sounding leads consist of a tip and measuring device. The latter may be in the form of a reel (steel or textile) or a wire rope with tags fastened at intervals of one metre (Fig. 29). Coarse cord is not to be used.

A cracker or whistle-cracker (a device like a small diving bell, or the same with a whistle attached), lowered into the bore by means of a measuring tape, produces a smack-

ing sound when coming in contact with the water. Accuracy of measurement comprises ±1-2 cm. Should any object (leaves, chips, etc.) be floating on the water of the bore, level measurement cannot be made.

To gauge the water level at large depths or where the use of a cracker is impossible (as when gauging the level in the space around the pipe column or in deflected or inclined wells) an electric device is employed (Fig. 30). It consists of a small case containing a reel with 100 metres of flexible insulated wire. To facilitate readings, the latter is provided with numbered tags at metre intervals, and blank tags at every half metre. One end of the wire is attached to the spindle of the reel and the other connected to an electrode. The latter consists of a brass rod 2-3 mm. thick, covered with rubber or ebonite insulation. To increase the weight of the electrode it is either attached to a 5-6 mm. lead plate (*a*) or enclosed within a round lead shell (*b*) (Fig. 30).

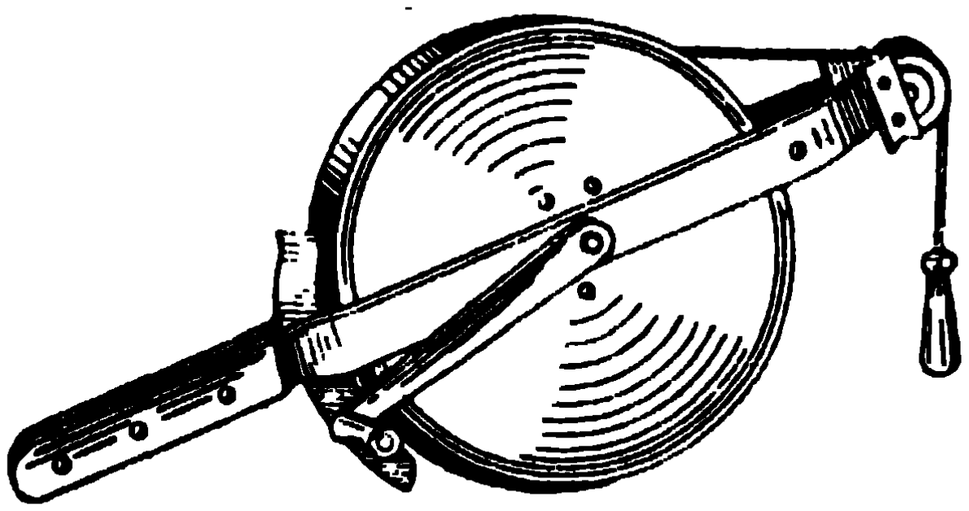

Fig. 29. Wire rope measuring reel.

The case contains a dry pocket-torch battery and a galvanometer or telephone indicator (Fig. 31).

The electrode is lowered so as to touch the bore casing. When it reaches the water the electric circuit closes and the galvanometer pointer deflects (if the device is supplied with an indicator, its black field turns white). The water level is then read off from the nearest numbered tag.

This same electric level-gauge is very often employed for dynamic level reading during test pumpings; to gauge the water level, a special observation tube of small diameter is lowered into the space around the pipe casing. The end of this observation tube should be 20-30 cm. below the mixer (airline).

For permanent observations, float gauges are recommended.

A simple and convenient device for systematic water level observations is the "tape level-gauge," designed by

E. V. Simonov (Fig. 32). This gauge is composed of a roller rotating freely on a thin spindle inserted in a clamp, and a tape, with centimetre readings, passed around the roller.

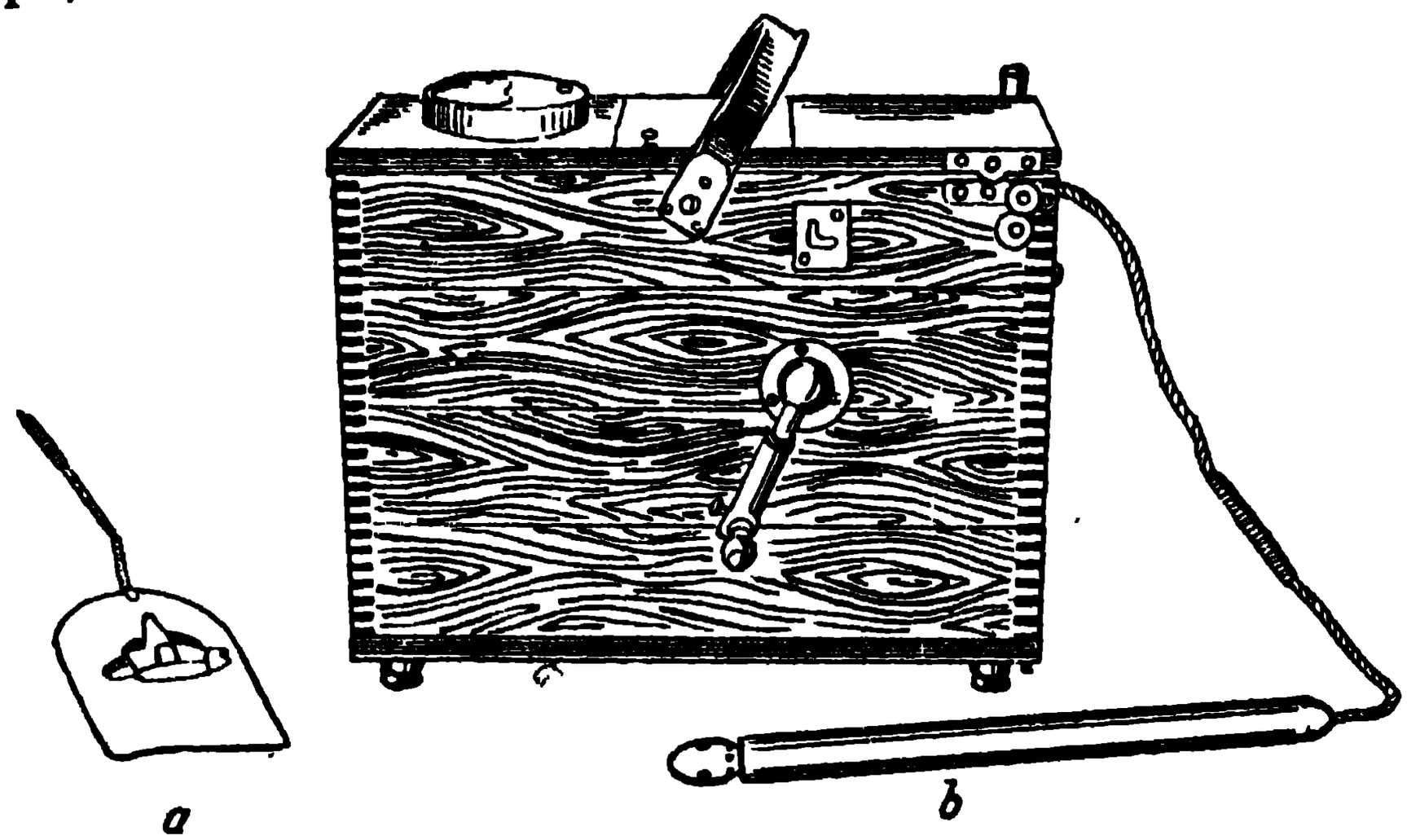

Fig. 30. Electric level-gauge.

A counterweight is attached to one end of the tape, and the other is connected to a string-wound bobbin, to the end of which a float is attached. The length of the string must ensure possible fluctuations of water level. Prior to setting up the tape level-gauge, the depth of the water table *H* is measured with the aid of a cracker or other instrument, after which the string is reeled off the spool so as to reach the water table. The tape is passed around the roller and the figure opposite the pointer on the clamp is taken as the zero reading (*O*). Subtracting from *H* the value of the reading *O*, a constant control level *C* for any given boring is obtained. Thus the control level is $C = H - O$..

To determine the water table level *H* in the course of further observations, it is sufficient to add the reading *O*

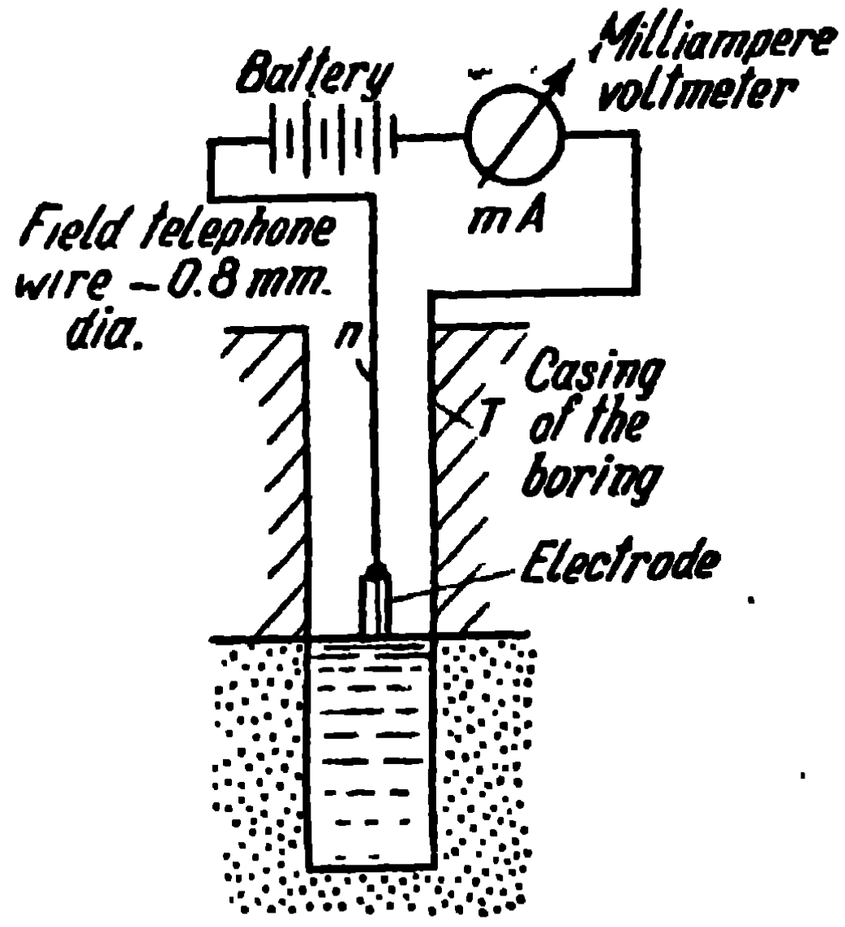

Fig. 31. Diagram of electric level-gauge.

recorded on the measuring tape, to the value C, since $H = C + O$.

The use of the tape level-gauge considerably shortens the process of level gauging and reduces the possibility of error.

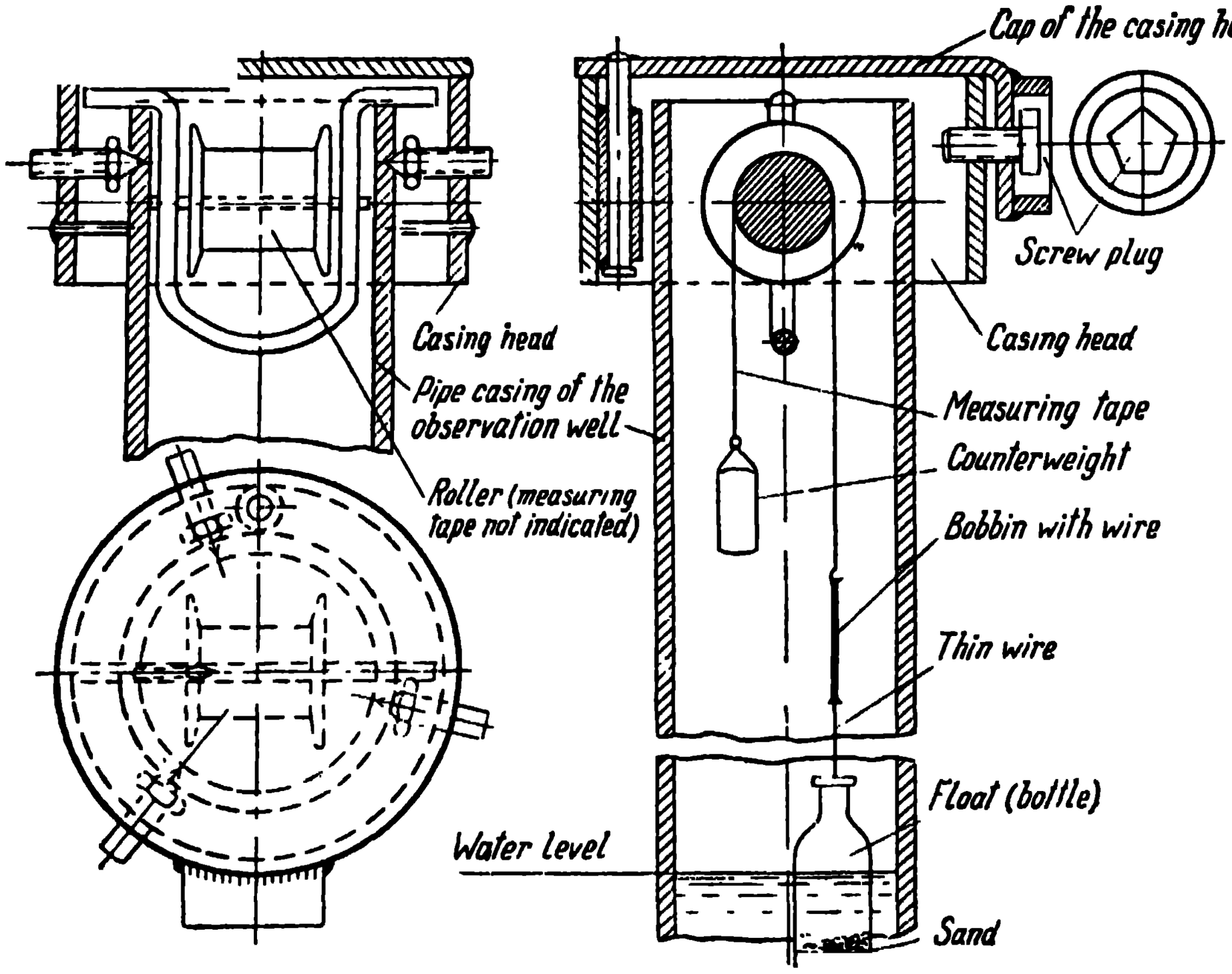

Fig. 32. Scheme showing set-up of Simonov's tape level-gauge in an observation well provided with a casing head.

If the water table rises or falls at a height greater than the length of the measuring tape, a corresponding length of string is reeled off the spool, this length then being added to the constant value C. If, aside from water level observations, the well is intended for temperature measurement or water sampling, the float is removed from the borehole and the string rewound on the spool.

To safeguard observation wells against tampering, a special casing head (Fig. 33) for use with the tape level-gauge is recommended, designed by E. V Simonov. This accessory consists of a shell made of a piece of bore pipe into which three or four bolts with steel points are screwed

heads inward. A branch pipe, welded on the inner wall of the shell, serves as a bushing for a rod welded to the cover. The latter is made of a steel disc with a shank containing a pentahedral bolt. This bolt can be turned only with the aid of a special pentahedral socket wrench. To carry out observations the bolt is removed and the cover swung aside by rotating it around the rod. Into the shell of the casing head under each bolt an iron pin is welded, preventing loosening from below.

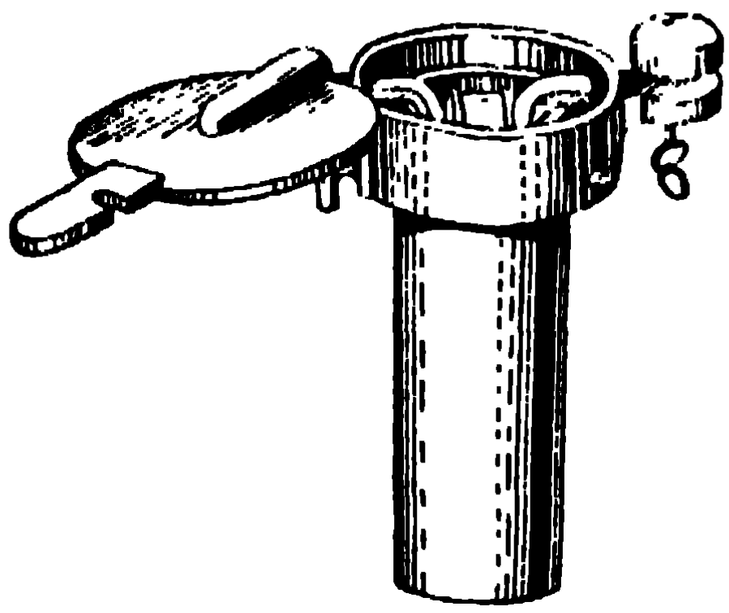

Fig. 33 General view of casing head and tape level-gauge.

A disc-type level-gauge, designed by Simonov (Fig. 34), obtains precise readings of water level changes in wells and may be used both for stationary observations and test pumpings. The device consists of an aluminium disc with a cord or thin wire wound about it. One end of the cord carries a float for lowering into the well. The disc rotates freely in its bracket, which is secured to a post, fastened in its turn to the edge of the pipe casing.

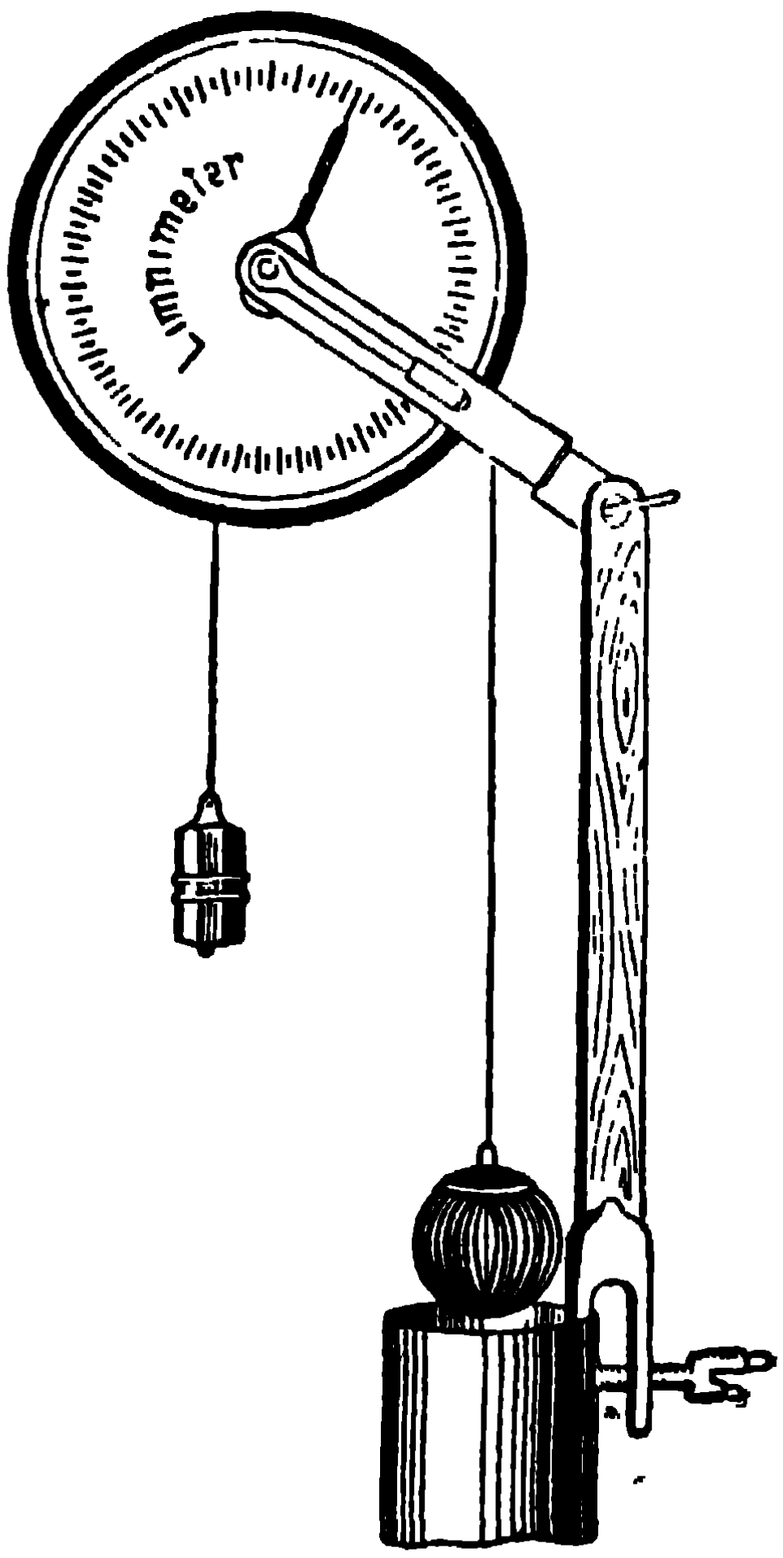

Fig. 34. Disc level-gauge on pipe casing.

Readings are taken with the greatest precision (± 1 mm.) and involve practically no time loss, thus permitting almost simultaneous observations in grouped wells.

50 mm. is the minimum diameter of the pipe casing with which the instrument may be used.

In systematic observations of changes in underground water levels hydrogeological practice usually employs the water-

stage recorder, the range of fluctuations being registered on squared paper pasted on a drum. The recording pen of the device is linked, in one way or another, with the float in the well (Fig. 35).

However, present-day developments in technique and telemechanics make it possible to concentrate all recorders of a given region at one of the central points and link them with the wells by wire or radio.

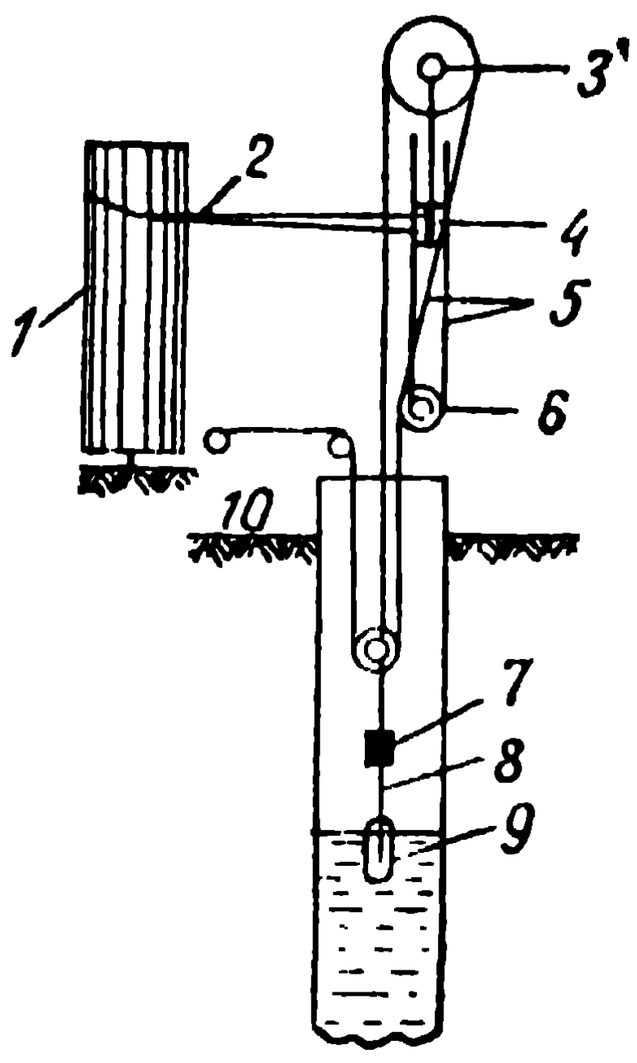

Fig. 35. Scheme of the 0-2 limnigraph.

1—drum; *2*—marker; *3*—scale pulley; *4*—carriage; *5*—post; *6*—guide block; *7*—counterweight; *8*—wire; *9*—float; *10*—winch.

For gauging the level of pressure waters, hydrogeological stations often employ operating wells equipped with piezometers; these are manometers whose calibration permits readings with an accuracy of up to 0.1 metre.

Apart from dynamic level measurements required during pumping operations, static levels should be gauged in operating wells. To do this, arrangements are made to halt pumping both in the well under observation and in neighbouring ones for the time required for recovery of normal level.

To measure the static level in flowing wells a special plugged casing head is fitted to the pipe casing and provided with a slide- or flap-valve and with a piece of pipe for installation of a manometer. If the pipe casing has no thread for fitting the plughead, a special pneumatic stopper, provided with a slide-valve and a piece of pipe for the manometer is installed. Pneumatic stoppers may be employed for low pressure-heads (10-15 metres above ground level).

B) INSTRUMENTS FOR MEASURING WATER TEMPERATURES

Special thermometers used for measuring water temperatures must satisfy the following requirements:

1) the thermometer must indicate the true temperature of the water in which it is submerged;

2) the instrument must retain its temperature indication for the time required to remove it from the well;

3) precision of the instrument should be within ±0.2° C;

4) the instrument must register its temperature reading for a certain predetermined time;

5) the instrument must be adaptable both for wells and springs.

Several different types are used in hydrogeological practice.

For deep waters, maximum and minimum thermometers are employed whose operation is based on the principles of the thermoelectric couple.

The instrument mostly used by hydrogeologists is the "lazy" thermometer; this is an ordinary glass mercury type enclosed in a brass case to safeguard it against impact (Fig. 36). The lower part of the case is widened to accommodate the bulb, and filled with copper filings. For deep borings, a material of low-heat conductivity is placed around the bulb, such as cork, rubber or paper. Before usage the "lazy" thermometer should be tested to ascertain the length of time it takes to respond to and retain a given temperature, after which care should be taken that the instrument is not removed too soon from the liquid into which it has been submerged.

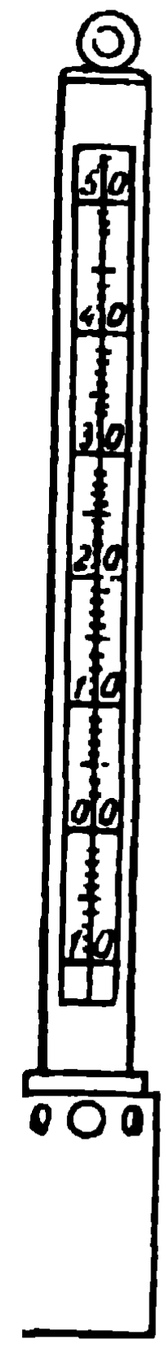

Fig. 36. Thermometer for measurement of ground water temperature.

Ordinary mercury thermometers are very much employed in practical work, being especially built for maximum inertia time. Tests conducted at the Koltushy experimental station have shown that the best results in this regard are obtained by mercury thermometers designed by AIMRM (All-Union Institute of Mineral Raw Materials); the cases of these instruments are provided with rubber tubing and finely cut cork for retardation of their action. The inertia time of these thermometers comprises 2-4 minutes for temperatures ranging from 18° to 33°; wind effect has proved insignificant. The use of such retarding materials as paraf-

fin and coal has shown negative results, their time of inertia being less than 10 seconds.

At the same station, tests to determine the speed at which a thermometer could be removed from the bore and the time required for readings have shown that the average hoisting speed with a reel from a 40-metre depth is equal to 78 seconds, and 48 seconds with a cord. Readings comprise 9-12 seconds, hence time spent in hoisting and reading total 80-120 seconds. Since a double ("safety") margin of inertia is required, the thermometer should have an inertia value of no less than 2.5 minutes. At present such conditions are satisfactorily met only by the AIMRM slow-acting thermometers. The negative qualities of these instruments include: need of prolonged exposure (about one hour), difficulty of insulation, large bulk and insufficient adaptability for measurements at depths of more than 50 metres.

The highest precision in temperature measurements is attained by the use of the electric thermometer; this is a combined thermocouple and sensitive galvanometer (millivoltmeter) whose calibration attains an accuracy of up to 0.1° C. A weighted thermocouple is lowered into the well by means of a duplex wire with tags attached at metre intervals. With this device it is possible to obtain constant and accurate recordings of temperature changes, for practically no time is required for the thermocouple to acquire the temperature of its surrounding medium.

For permanent study of temperature changes, self-recording thermometers are employed.

c) APPARATUS FOR THE COLLECTION OF WATER SAMPLES

Sampling for chemical analyses, both of free ground and deep waters, entails the use of special apparatus which must satisfy the following demands: firstly, the device must not churn the water column in the borehole and must be able to collect a sample from a given and precisely determined depth; secondly, it must close tightly to prevent escape of gas in the water being sampled. E. V. Simonov of the All-Union Institute of Hydrogeology and Engineering Geology has taken these requirements into account

in his designs, one for drawing water samples ("the water carrier"), and another—a telescopic type—for sampling both water and gas at great depths. Tests of the equipment have shown satisfactory performance.

The water carrier can draw water samples from boreholes at any given depth and may be used both while drilling the wells and during systematic study of the chemical regime of underground waters (Fig. 37).

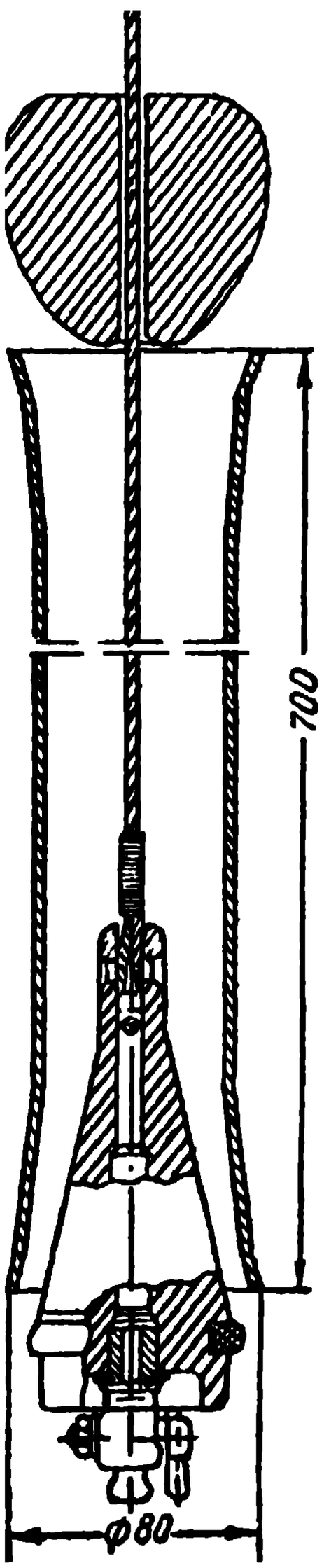

Fig. 37. Simonov's "water carrier."

Fig. 38. General view of the "water carrier."

Fig. 39. General view of the telescopic depth sampler.

The device consists of a reception cylinder, weight, and pilot plug.

The reception cylinder is in the form of a pipe open at both ends, with a lip in its lower part into which a rubber packing ring is pressed. The weight is tapered and made of iron or some other metal. When sampling, the weight is lowered to the given depth with the aid of a thin steel wire. The reception cylinder then follows along the same wire. As the cylinder progresses down the well the water washes freely through it and, as it reaches the weight, takes the water sample. The rubber ring ensures a reliable seal while hoisting the device to the surface. Two types have been designed:

1) for wells with a diameter of 75 mm. and more, and with a 1.5 litre capacity;

2) for wells with a minimum diameter of 50 mm. and more and with a capacity of 0.6 litres.

A general view of the water carrier is given in Fig. 38.

The double-valve bailer or sample collector described above is for chemical analysis of water.

Up to the present the technique of drawing liquid and gas samples has been unsatisfactory and often led to erroneous conclusions.

The telescopic depth sampler for both water and gas as shown in Fig. 39 possesses the following features:

1) water and gas can be drawn from a precisely determined depth, the device's design preventing penetration of water from overlying horizons;

2) sample volume equals 1.5 litres;

3) the sample enters the device evenly under a low constant pressure;

4) the instrument is equipped with an appliance ensuring the access of spontaneous gas bubbles;

5) the pressure within the device upon coming to the surface does not differ from that of the latter by more than 0.3-0.5 atm. and can be brought to atmospheric pressure;

6) water samples are drawn with all their dissolved gases;

7) the proportions of gas and liquid contained in the sample can be determined immediately;

8) the sample can be transferred to another vessel (for dispatch to the laboratory) under a constant pressure differing very slightly from atmospheric.

To sample water containing practically no gas the use of the water carrier is advisable, whereas the telescopic collector should be employed for water with a high proportion of dissolved gases.

4. SCHEDULE OF OBSERVATIONS OF THE LEVEL AND DISCHARGE OF UNDERGROUND WATER

In order to establish definite laws governing variations in level and discharge of underground waters, there should be a definite schedule of observation.

To do this rationally, the first two or three years should be devoted to daily measurements at specially selected points with representative natural conditions reflecting all the features of occurrence, recharge and movement of the underground waters, but not including artificial factors (water intakes, hydraulic structures, etc.). Measurements at other (not typical) points during this period should be limited to ten times a month.

Readings should be taken regularly and at a fixed time for each post, the daily recordings at the special points to be repeated three times each day.

On the basis of these observations, comparable diagrams should be drawn showing changes in level according to various frequency of measurement. Curves are plotted on these diagrams illustrating changes of the following factors: precipitation, air and water temperatures, moisture deficit and absolute humidity of the air, barometric pressure, water reserves in the snow cover, and water levels of rivers connected with phreatic sources. For waters occurring at a shallow depth temperature curves are plotted for the soil ground.

By analyzing such comprehensive diagrams the character of underground water fluctuations are revealed both for periods of one year, and for many years running,

and the factors giving rise to these fluctuations are established.

This analysis will also determine a rational schedule of observations for different sections of the territory under study, depending upon geological structure, geomorphological features, depth of underground water occurrence, as well as upon the interrelation between level fluctuations of the latter and their immediate causes.

It should be borne in mind that in some areas the frequency of measurements will differ according to season of the year and natural features. The higher the range of level fluctuations, the more frequent should be its gauging. For example, at observation points situated along riverside tracts, there will be considerable fluctuations during high river, and the contrary during periods of low water. At observation points situated in large irrigated areas, sharp fluctuations in the level of underground waters are usually observed at times of irrigation and plant vegetation. The same may be said of snow melting periods at points located where there is a shallow depth of the ground water table. During periods of large phreatic fluctuation, measurements must be conducted once a day.

As compared to free ground waters, fluctuations in level and discharge of artesian waters is usually less hectic, excepting in their intake area where these waters are unconfined and do not differ in any way from free ground waters. All these peculiarities must be taken into consideration when establishing a logical sequence of measurements.

A clear picture of the natural peculiarities of each observation post will be required when the obtained data is being processed and analyzed. Such a picture should also distinguish natural from disturbed features of the underground water regime.

In areas where this regime is closely associated with artificial factors its study should chiefly embrace (aside from general problems) its dependence upon discharge of operating wells, upon water disposal from mines, and upon discharge from drainage structures; the study should also include the character and amount of irrigation, variations in reservoir horizons, etc. This will clarify the relationship

at any given period between underground water level and the development of depression cones and water domes on the one hand, and the amount of water drawn from (or fed to) the aquifers on the other hand.

5. METHODS OF STUDY OF UNDERGROUND WATER TEMPERATURE

Temperatures of underground waters are part of the complete range of studies relating to the regime of underground waters.

The temperature of underground waters and its chronological variations depend upon a number of factors: climate, terrestrial heat, chemical and biochemical processes, percolating atmospheric precipitates, surface streams, filtration properties of the rock, velocity of underground flow, fluctuations in water level, the economic activities of man, and a number of other factors.

With the aid of a temperature fluctuation diagram it is possible to establish the dominant factor determining the character of temperature variations at any given observation point. For example, typical for artesian waters is its insignificant range of seasonal temperature fluctuations, a range where the average annual temperature of these waters is usually several degrees higher than the average annual temperature of the air in the given region, the basic factor here being terrestrial heat.

To establish the types of thermal regimes for free ground waters is customarily far more difficult because of the many factors simultaneously involved. The dominant factor acting above the so-called zone of constant temperature is climate, for climate creates the zones along the vertical cross-section. Furthermore, artificial factors are often also active and sometimes even assume the dominant role (aquifer extraction, amelioration measures, hydrotechnical construction, etc.).

The study of underground water temperatures within certain periods of time assists both in disclosing the formation of underground waters in any particular water-bearing stratum and in forecasting its regime.

Changes in such temperatures influence the variations in physical and chemical properties of the water. It is known, for instance, that with an alteration in temperature, the water's volume also changes. With an increase in temperature the dissolving capacity of the water proportionately grows, leading to a corresponding increase of its general mineralization and sometimes to a change in the component ratio.

All these phenomena should be taken account of during the study.

The aims of investigating chronological changes in the temperature of underground waters are:

a) to give a proper appraisal of the water's quality for purposes of economic utilization (water supply and irrigation);

b) to disclose the interrelation existing between temperature changes, variations in chemical composition, and level fluctuations;

c) to reveal the relations of aquifers with each other and with surface waters;

d) to draw up a time forecast of temperature changes of the water.

The temperature at different depths in one and the same aquifer is not uniform, nor are the laws governing its variations the same.

In the upper zone of free ground waters the range of annual temperature fluctuations is very great. The results of observations conducted by A. V. Lebedev at the fixed observation station of the All-Union Institute of Hydrogeology and Engineering Geology near Moscow may serve as an example (Fig. 40).

Observations were carried out in a group of wells sunk to various depths. The diagram shows that the water temperature in the upper zone showed the greatest fluctuations. With penetration into the deeper water-bearing stratum, temperature fluctuations declined, and at an approximate depth of 18 metres became very negligible. At greater depths there were almost no further alterations.

The purpose of our study (as noted above), as well as the differences in water temperature along the vertical cross-section, show the need of a careful approach to the organization of such investigations.

Observation bores must be representative with regard to depth and cross-section and should, for example, feature temperature variations along the profile stretching from the intake area towards the discharge zone.

Only boreholes and springs may be used as observation points; dug pits are not allowed, since they appreciably

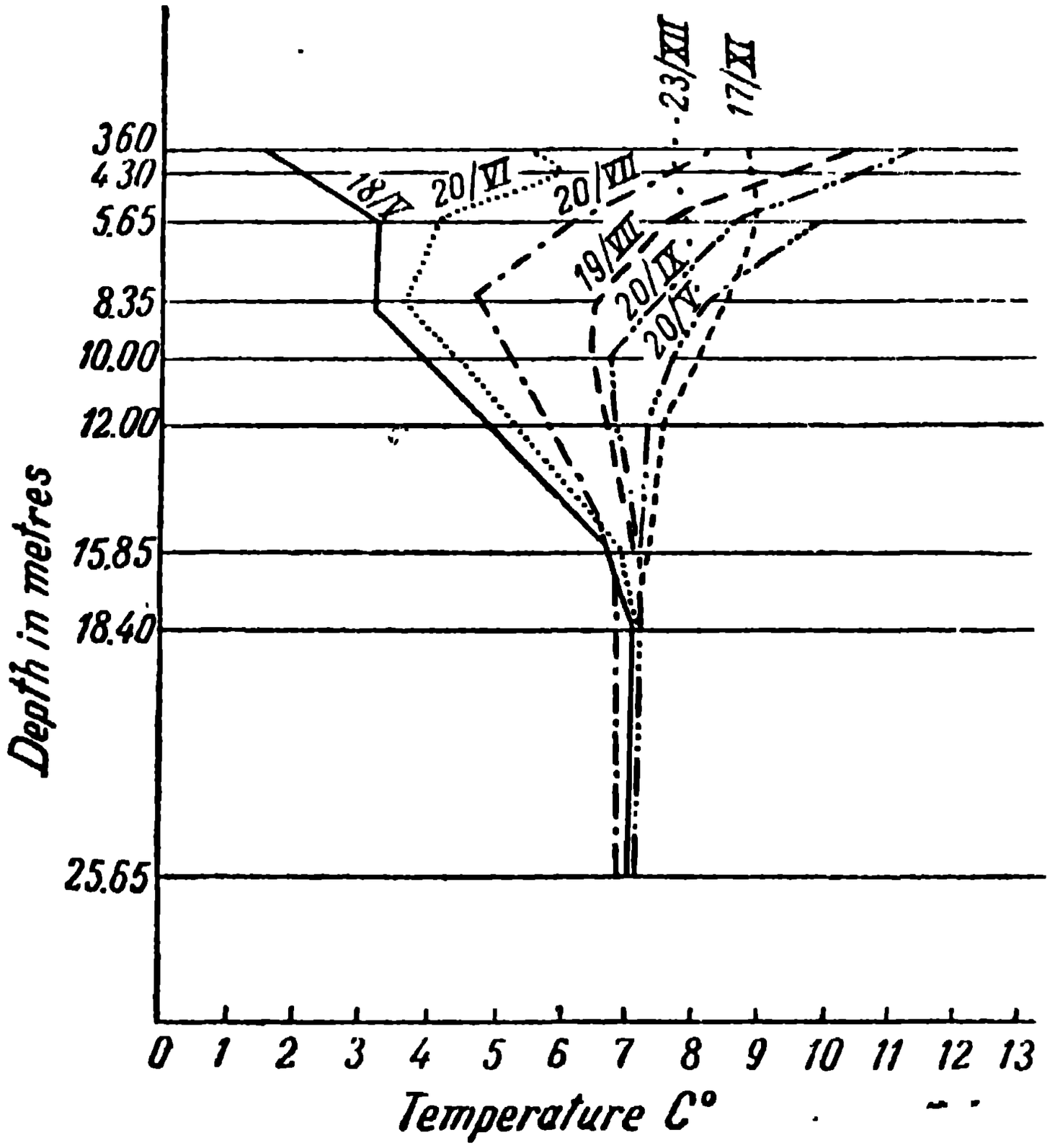

Fig. 40. Curves of ground water temperature in an aquifer (according to A. V. Lebedev).

distort the temperature of the water. Thus at the permanent observation station of the AIHEG near Moscow A. V. Lebedev observed a sharp difference in water temperature in a pit and a neighbouring borehole. The pit, covered with a wooden lid, showed a water temperature 1.2°C higher than in the bore. In hot climates this difference may be still greater.

Even in specially equipped boreholes there is a certain equalization of temperature through convection, but observations have proven this difference negligible.

Three types of observation points are encountered (each repuiring an approach of its own):

1) specially equippel borcholes;
2) ordinaıy hydrogeological boreholes;
3) operating wells.

In specially equipped borings, properly insulated from all atmospheric influence, the filter should pass through the entire thickness of the aquifer. Equalization of water temperature through convection at such points is very insignificant, this having been clearly proven by observations effected at the stationary observation point of AIHEG near Moscow.

Recordings should be carried out simultaneously at different depths. All subsequent measurements should be made at the same depth, measured from the mouth of the well.

Frequency of recordings will be determined by the nature of underground water temperature changes and their range.

To analyze temperature changes within any given territory, readings at regular hydrological borcholes should be grouped and the thermometer lowered to the filter level. Measurement should be conducted when the water is undisturbed by pumping.

Measurements in permanently exploited wells should be made at filter level via the annular space on the outer side of the pipe. When direct readings are impossible, the thermometer should be placed at the mouth of the bore under the water jet. Such temperature recordings will be somewhat distorted, but in prolonged studies they are helpful to a certain extent in determining the character of temperature fluctuations.

When investigating temperature variations in springs, observations should be effected directly at their outcrop. When analyzing the data thus obtained the character of outflow should be taken into consideration.

We emphasize in conclusion that all information gleaned from temperature study of underground water must be considered in combination with variations in level, yield and chemical composition of the water.

6. STUDY METHODS OF CHANGES IN CHEMICAL COMPOSITION OF UNDERGROUND WATERS

One of the principal tasks of hydrogeological stations in their inquiries into the laws governing regimes of underground waters is the study of chemical changes of these waters.

A) PROBLEMS TO BE SOLVED

The following questions are included in our study of chronological and positional changes in chemical composition of underground waters:

1) to assess the quality of underground waters with regard to utilization for water supply, irrigation, etc., and to disclose the laws governing quality changes both chronologically and positionally (time and space);

2) to disclose the corrosive (aggressive) action of the water against structures, pumping equipment, etc.;

3) to reveal the influence of artificial factors (irrigation, drainage, extraction of waters from aquifers, etc.) on changes in chemical composition;

4) to determine reclamation possibilities of land areas; chemical composition of underground waters might not only influence salinization of the land, but also indicate a tendency towards the formation of white and black alkali soils, deterioration or improvement of drainage conditions, creation of surplus moisture, etc.;

5) to determine the condition of the rock in mine workings for forecasting heaving, fall-in's, disastrous water inrush, etc. Destruction of rock is the result of intensive oxidation, the products of which, as well as the oxidation itself, change the chemical composition of underground waters. The results of such studies will therefore be the basis for the above-mentioned forecasts;

6) to disclose the role of underground waters in the formation and destruction of mineral deposits;

7) to precisely determine the hydrogeological conditions of the region under study (recharge and discharge, relationship between individual aquifers and between these and surface waters as well as time variations in such relationship);

8) to investigate the laws governing the development of chemical composition of underground waters;

9) to compile forecasts of changes in chemical composition of underground waters; these are classified into long-range, short-term and episodic forecasts.

All variations in chemical composition of such underground sources should be studied together with other elements of their regime.

B) WATER SAMPLING SITES

To analyze the chemical composition of the water in an aquifer and the surface streams and basins that might be connected with the former, representative observation points should be chosen to cover each distinct portion of the aquifer. When these points cover a considerable territory they should be distributed so as to aid in drawing up profiles extending from the intake area to that of the natural discharge of the underground flow.

Water may be sampled from:

1) boreholes specially sunk for examination of chemical composition changes (experimental groups);

2) ordinary hydrogeological observation points (boreholes and springs);

3) exploited wells whose bore logs are known. The diameters of filters must permit the introduction of the water sampler.

A large number of observation points should be on hand during initial stages of inquiry into the chemical regime of subterranean and surface flow. This number may be reduced with the accumulation and digestion of data.

For a proper conclusion as to chemical changes along the vertical cross-section, samples should be drawn from different levels. Chemical variations at different depths are particularly evident in the free ground waters of Central Asia. When drawing samples the location of filters should always be taken into consideration.

Several bores should be sunk at different depths and at intervals ranging from 1.0 to 1.5 metres, with filters placed at different elevations: 1) within the zone of long-

term level fluctuations; 2) below the water table at depths of 1.5-2.0, 3.0-4.0, 5.0-6.0 metres, etc.

The first two or three years of such observations conducted by hydrogeological stations of Central Asia have already supplied some very interesting data.

C) WHEN WATER IS TO BE SAMPLED

The rate of chemical changes in underground waters is chiefly contingent upon the following factors:

1. Ratio of recharge between diverse sources of ground water in the given area (percolation of atmospheric and surface waters and underflow) and intensity of outflow along the water-bearing stratum;
2. Dissolution of salts accumulated in the capillary zone; this is observed during the rise in ground water level;
3. Oscillations of barometric pressure (in mine workings this concerns changes in conditions of ventilation); these variations provoke changes in the partial pressure of gases and this, in its turn, changes the chemical composition of the underground water;
4. Changes in temperature of the water; with such alterations the solubility of the various components composing the rock of the aquifer also changes. Temperature variations of the water may also indicate changes in oxidation intensity;
5. Changes in the intensity and duration of pumping operations;
6. Changes in intensity of oxidation processes.

The time set for observations will depend upon the above factors and upon the degree of detail the search is to be subject to, the latter including a chemical analysis of the underground waters.

If these waters are free from artificial disturbances, sampling for chemical analyses may be conducted once a month. More frequent sampling should be conducted when other factors make themselves strongly felt (either as already enumerated above or in Chapter 1).

When such influences involve artificial factors (irrigation, water extraction, drainage, etc.) sampling should be conducted more frequently in order to determine the

character of the above causes and their degrees. More sampling should be done, and from a greater number of observation points, during the first few years of observation. Sampling during the first, and possibly during subsequent years, should not only embrace periods of absolute maximae and minimae but also those of relative maximae and minimae.

In subsequent years, when the general trend of underground level fluctuations will have become sufficiently clear and the relation of these fluctuations to variations in chemical composition of underground waters will have been definitely established, the quota of water sampling may be reduced. In such cases samples should be collected during absolute maximae and minimae, and also when changes in chemical composition are not quite clear or present a definite interest in connection with analyses obtained from previous observations. If the inquiry concerns the relation to surface waters, samples should be drawn at the moment of high level of aboveground waters, with two or three additional samples taken during the following three or four months (depending upon the remoteness of the surface stream from mine workings and upon filtration properties of the water-bearing stratum).

Besides borings specially selected for chemical examination, samples should be collected not less than four times a year from all observation points and the drawings should coincide with the most typical water level positions.

When chemical composition of underground waters involves oxidation of the rock in regions of mineral deposits, the water should be sampled during sharp changes in water discharge as well as when there is a notable increase of loading of mine props.

Samples should also be taken during the changes in water temperatures, particularly if such changes are positive (rising temperature).

D) CONDITIONS AND METHODS OF WATER SAMPLING

When drawing water samples for chemical analysis, the following should be borne in mind:

1. When ground water issues at the surface, its natu-

ral environments become radically changed, gases are released (primarily free CO_2), oxidation occurs (for example the transformation of $Fe^{\cdot\cdot}$ into $Fe^{\cdot\cdot\cdot}$), and there are subsequent changes in the value of pH. These processes result in alterations of the water's chemical composition. The thinner and smaller the issue of water, the more intensive and faster will the course of these processes be. This determines the requirements for water sampling from springs and from mines. Samples must be drawn directly where the water leaves the rock and where the flow is most concentrated. In mine workings, water samples should be taken from stemmed filters.

2. Water that has stood for a long time in the mine becomes degased. Organic matter contamination of the workings may lead to the process of sulphate reduction, which results in a change of content of the ions of SO_4'', $Ca^{\cdot\cdot}$, Mg, free CO_2 and pH. Furthermore, with a shallow depth of the ground water table in pits and dug wells, an intensive evaporation may set in and the utilization of these sources for observation is not to be recommended. As a rule, water samples should be collected from boreholes which are first subjected to a preliminary pumping.

3. Very often the chemical composition of underground waters in one and the same aquifer varies with depth. For example, if the ground water table is shallow with a resultant intensive evaporation, a layer of water with a higher degree of mineralization is formed in the upper zone, while if there is intensive infiltration of surface waters this layer acquires additional water with a low degree of mineralization (fresh water lenses). Underground waters circulating in the same rock may be of different chemical composition depending upon the velocity of circulation. When choosing the depth of boreholes used for water sampling, these facts as well as the size of the stemmed filters in mine workings should be taken due account of. The volume of water pumped out prior to sampling must comprise from 1.5 to 2.0 volumes of the water column in the well.

When drawing water samples from a battery of wells, collection of samples should commence with the well of the least depth. The same is true with regard to stemmed

filters. Water may be sampled both in regime-study borings and in mine workings at points of water outcrop from stemmed filters, but should not be drawn from open streams and basins situated in mines.

4. Samples should be taken from boreholes at filter depth with the aid of a water sampler.

When sampling springs and flowing wells, a bottle may be used. All sampling operations must comply with prescribed instructions for chemical analysis sampling, compiled by V. A. Priklonsky and F. F. Laptev in 1949.

5. Changes in chemical composition of the water also take place in the vessel used for its collection. The intensity of such processes increases with a corresponding increase of the time lapse between drawing and analysis, with a rise in temperature of the medium surrounding the sample, with a faulty container stopper, with an increasing difference between pH value and the neutral reaction, and with a greater difference between the redox potential of the water and the oxidizing properties of the atmosphere. Organic matter in the water provokes sharp changes in connection with processes of sulphate reduction. The intensity of changes in different components of mineralization also varies considerably. Dissolved gases pH and HCO'_3 are subject to the greatest changeability and should be determined directly at the water sources. In order to avoid the oxidation of $Fe^{\cdot\cdot}$ into $Fe^{\cdot\cdot\cdot}$ and the transformation of ions into colloids, these contents should be analyzed at the sampling site. When storing water in a glass vessel the content of silicic acid may increase due to dissolution of the glass.

When the sample is stored in a vessel, a part of the mineralization components precipitates ($Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, Fe). Therefore, both the water and precipitates should be subject to laboratory analyses. Hence the absolute necessity of preventing the access of rock particles into the water sample.

Heavy metal components are adsorbed very intensively by the walls of a vessel, and it is very difficult to separate them in the laboratory. Therefore, water samples for determination of heavy metals should be collected separately. Water that is to be examined should be acidified im-

mediately upon drawing with the aid of chemically pure sulphuric acid that has been checked for the absence of heavy metals. To suppress the processes of sulphate reduction, one millilitre of chlorophorm or toluene should be added to each litre of water.

Special methods for the preservation of water samples are described in a manual compiled by V. A. Priklonsky and F. F. Laptev in 1949.

If the aim is spectral analysis a dry residue should be obtained on the spot by evaporating the sample in platinum or porcelain cups (with all due precautions taken), for water stored in glass containers may become enriched with microcomponents.

Each water sample must have a detailed tag attached, from which may be ascertained: geological and hydrogeological conditions of the water-bearing stratum, the point where the water was sampled, level, discharge and temperature of the water and its physical properties at the time of drawing, influence of artificial factors, conditions under which the water sample was collected, etc. Both the dates of collection and analysis should be noted on the tag.

E) LIST OF CHEMICAL ANALYSES OF UNDERGROUND WATERS

The following analyses are to be made of water samples

1. Cl′ (chlorine-ion); due to the high solubility and low level of hydrolysis of all chlorides, the chlorine content in the water is extremely stable; as compared to other components it is the least liable to changes caused by its composition, or by mineralization, temperature and pH value. The chlorine-ion content is likewise very little dependent upon the redox potential. Therefore, the content of Cl′ characterizes in the main the length of the circulation route of the water and the intensity of water exchange. Chlorine content sharply increases under conditions of difficult water circulation in the rock. Increased Cl′ content may be due to water pollution. Cl′ content is a typical feature in determining waters coming from different water-bearing strata and its analysis is therefore obligatory in all cases.

2. SO''_4 (sulphate-ion); the presence of this ion in underground waters is a good indication of the rate of oxidation processes, which quite frequently are accompanied by the transition of insoluble sulphides into soluble sulphates.

This ion is relatively easily adsorbed by colloids, mostly by iron colloids. Low pH value prevents adsorption. Under reduction conditions (in the presence of organic matter) the SO''_4 ion dissociates, forming H_2S and CO_2. The considerations cited above should not be forgotten when applying SO''_4 for disclosing the connection of aquifers with each other and with surface bodies of water.

3. HCO'_3, CO''_3, free CO_2; the HCO'_3 ion in underground waters is directly dependent upon the partial pressure of free CO_2 in the environment and upon the pH value. With the usual composition of CO_2 in the air contained in the soil, the content of HCO'_3 in underground waters does not exceed 300-400 milligrams per litre. Higher figures will show that the water either contains sodium carbonate (HCO_3 in solution balanced with Na ions) or that there is an additional source of carbon dioxide enrichment of the water and of the medium surrounding it. Sometimes these additional sources are due to processes of putrefaction in contaminated dug wells, boreholes and pits. HCO'_3 content in the same aquifer is liable to very considerable fluctuations.

The existence of free CO_2 (gas) in water and in the ambient medium is influenced to a very high degree by a number of factors, such as temperature, barometric pressure, the nature of interstices in which water is circulating, gas perviousness of the surrounding rock, velocity of underground water movement and the biological activities of living organisms. Therefore HCO'_3 in water formed under the influence of CO_2 may be subject to a wide range of fluctuations. Variability of the HCO'_3 content is likewise associated with the fact that the differentiation of the carbonic acid in accordance with its individual types (free CO_2, HCO'_3, CO_3) and with its total unchanged amount, is dependent upon the pH value, and this latter, in its turn, is also subject to very strong fluctuations. Thus, an investigation of variations in HCO'_3 ion content cannot serve as a criterion for the establishment of the relation of water-bearing strata with each other and with surface waters.

But the determination of HCO'_3 is obligatory in each analysis because

a) only in this way is it possible to ascertain whether the water in question contains sodium bicarbonate;

b) when determining HCO'_3 it is possible to estimate the content of $Na^{\cdot} + K^{\cdot}$ by the difference between the sums of milligram equivalents of anions and cations;

c) the correct determination of free CO_2 may be verified by the magnitude of the HCO'_3 and pH content, or in accordance with HCO'_3 and free CO_2 a correct determination of pH may be made;

d) carbonic acid together with any other weak acid forms heteropoliacids which raise the oxidation potential of heavy metals and thus retard the process of oxidation.

4. $Na^{\cdot}$ (sodium-ion); all $Na^{\cdot}$ compounds possess a high degree of solubility. Therefore, aside from the lithological composition of the rock, the $Na^{\cdot}$ content in the water depends principally upon the intensity of water exchange and the extent of its circulation. But the $Na^{\cdot}$ content is also contingent upon other circumstances. For example, the solubility of Na_2CO_3 and $NaHCO_3$ varies considerably with changes in temperature. $Na^{\cdot}$ is subject to base exchange. Therefore, when using the $Na^{\cdot}$ content to determine the interrelation of aquifers with each other as well as with surface waters, these two circumstances should be duly considered.

5. $Ca^{\cdot\cdot}$ (calcium-ion); the proportion of $Ca^{\cdot\cdot}$ in underground waters is usually insignificant and only in highly mineralized oil-field waters does its content increase sharply, since the major part of $Ca^{\cdot\cdot}$ is balanced in the solution by a large chlorine content. In other waters, $Ca^{\cdot\cdot}$ may show a relative rise with a decline in pH, an increase in the partial pressure of CO_2, as well as with a reaction of free H_2SO_4 on the limestone. The additional content of $Ca^{\cdot\cdot}$ formed in the latter manner may be retained even following the neutralization of sulphuric acid, giving rise to an increase in pH value. When employing the $Ca^{\cdot\cdot}$ content as an indication of the interrelation of water-bearing strata, both the aforegoing facts and the susceptibility of $Ca^{\cdot\cdot}$ to exchange adsorption should be considered.

6. $Mg^{\cdot\cdot}$ (magnesium-ion); waters with a predominance

of $Mg^{\cdot\cdot}$ are encountered relatively seldom. This is because $Mg^{\cdot\cdot}$ is easily combined in insoluble magnesium silicates. An increased content of $Mg^{\cdot\cdot}$ in waters mineralized up to 50-70 grams per litre may occur only during the formation of "soda" waters, which are themselves enriched with $Mg^{\cdot\cdot}$ by the peptizing of silicates. Increased magnesium content in highly mineralized waters is indicative of a base exchange proceeding between the calcium dissolved in the water and magnesium taken up in the absorbing complex of the rock, both deposited and existent in the highly mineralized water medium.

7. SiO_2, SiO''_3, $HSiO'_3$ (colloids and ions of silicic acid); ordinarily, the content of silicic acid in underground waters is negligible (5-20 milligrams per litre) but rises in thermal waters and with an increased pH. Under such conditions silicic acid may be present in the form of $HSiO'_3$ and SiO''_3 ions, and in all other waters in the form of SiO_2 colloids. Other conditions being equal, SiO_2 content will be higher in waters circulating in open fissures and voids and lower in those circulating in the rock pores.

In processes of intensive oxidation, that cause rock decomposition, mine waters may become enriched with silicic acid. Increased silicic acid content in mine waters contributes to a less intensive adsorption resulting from a lower pH value and the presence of a large number of open fissures and voids in which the water is circulating.

In this way an increased content of silicic acid may point to a higher temperature and water alkalinity due to its circulation through deep structural fractures, to an intensive decomposition of the rock as a result of strong oxidation processes and, particularly, to decomposition of the silicon cement or the skeleton of many kinds of rock.

A determination of the content of silicic acid in the water is likewise important for estimating the physico-chemical conditions attending the oxidation process of heavy metals and, consequently, any changes in their solubility. Silicic acid, being a weak acid, acts together with other weak acids to form heteropoliacids which raise the oxidation potential of metals.

8. Fe_2O_3, $Fe^{\cdot\cdot}$, $Fe^{\cdot\cdot\cdot}$ (colloids and bivalent and trivalent iron ions); hydrocarbonates, carbonates, sulphates

and chlorides of iron possess a relatively high degree of solubility, but the amount of iron in the water is usually small because ferric ions are hydrolyzed and pass into insoluble ferric hydrooxide when pH=5. Ferrous ions also pass into insoluble hydrooxide when pH=7. Hence, a high iron content may be found only in mine waters, as well as waters linked with swamps and peat bogs (low pH values), and also in certain deep-lying waters under reduction environment. Large quantities of iron (particularly trivalent iron) in mine waters bear testimony to the decomposition of rock occurring during the process of intensive oxidation. Very often iron is present in the water in the form of colloids. The ratio between bi- and trivalent iron shows the intensity of transition from conditions of reduction to those of oxidation. In waters where pH approaches 7, very negligible quantities of iron may be present in the form of colloids.

9. Al_2O_3, $Al^{\cdots}$ (colloids and ions of aluminium); these hydrolyze and precipitate from solutions at still lower pH values (4, 2) than in the case of iron. Ordinarily, the aluminium content in the water is very insignificant and is principally found in the form of colloids. In mine waters the aluminium proportion may rise to hundreds of milligrams per litre, which, like an increased iron content, serves as evidence of intensive decomposition of the rock.

10. $Mn^{\cdot\cdot}$ (manganese); the conditions pertaining to migration of manganese in underground waters have not yet been investigated sufficiently.

The most favourable circumstances for the presence of manganese in underground waters are reduction conditions at a low pH value. Under such conditions the content of manganese attains hundreds of milligrams to the litre, while in surface waters it is usually contained in quantities not exceeding 5 milligrams per litre.

A heightened manganese content is characteristic of waters circulating in the zone of cementation or at the boundary line between the oxidation zone and the zone of primary ores where the process of oxidation has but begun.

11. Trace-components. Trace-components include those elements whose content in most natural waters is negli-

gible because of their scarcity in the rock or poor stability in underground waters.

Investigations of migration conditions of trace-components have so far been very limited. It may only be noted that the presence of lithium in underground waters serves as evidence of their circulation at heightened temperatures through fissures in the proximity of granites and pegmatite veins or in sedimentary rock appearing as products of decomposition of the former. In its most soluble compounds, titanium is widely prevalent in the soil and its content in ground waters therefore very often rises. At the same time titanium in the water may be due to the leaching of iron ore. The presence of beryllium is sometimes proof of far-reaching destruction of the crystalline skeleton of the rock.

The study of trace-components in underground waters helps to solve problems concerning the interrelations of individual aquifers.

An inquiry into trace-components (chiefly fluorine, arsenic and heavy metals) is also absolutely essential for establishing the possibility of utilization of the water for drinking supply.*

Mine waters with heightened heavy metal content are very corrosive.

12. Gases. Besides the determination of free CO_2, analysis must also be made of O_2, H_2S and CH_4.

When determining the O_2 content in water it should be remembered that oxidation processes may proceed not only at the expense of dissolved oxygen, but will also be due to such active oxidants as Cu^{+2}, Mn^{+4}, etc., and that oxygen is very much consumed during oxidation of organic matter.

Hydrogen sulphide suggests the presence of reduction conditions in the water; it may point to the existence of cementation zones or primary ores in the metal deposits. But H_2S in the water may also indicate processes of desulphation. If there is organic matter, CH_4 characterizes the zone of reduction conditions in coal deposits.

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*State Standards have established the following maximum content limits (milligrams per litre): F-1.0, As-0.05, Rb-0.1, Cu-3.0, Zu-15.

7. METHODS IN UNDERGROUND WATER INVENTORY AND THE STUDY OF THE ZONE OF AERATION

A) GENERAL REMARKS

Variations in the regime of ground waters conditioned by the active intervention of man in a given territory are indicated by a rise or drop of the water table and changes of chemical composition and dynamic sources of ground waters. Forecasts of such variations are made possible by an inventory of underground water (study of the water balance).

Such an inventory opens the way to investigations of the process of phreatic development and discloses the principal genetic relations between the elements of the water's regime and its active factors.

The definite aims of our study are:

a) to determine the sources of free ground water for water supply;

b) to fix the rate of water expenditure for maintenance of an optimum water regime in irrigated territories;

c) to appraise land conditions with regard to reclamation measures, etc.

The free ground water inventory should be preceded by a detailed geological investigation and by the organization of comprehensive observations of the phreatic regime.

Before beginning the inventory in a given region, a clear understanding must be had of its principal aims.

The zone of aeration is a very important factor in an all-embracing study of the regime and balance of free ground waters. Water percolating from the surface of the ground accumulates in this zone and under given conditions is expended in phreatic recharge. In this connection it is very important to determine the process of water percolation in the zone of aeration.

B) BASIC ELEMENTS OF THE GROUND WATER INVENTORY

The basic elements in the balance of ground waters include (increment of free ground waters W_1 metres per day):

atmospheric infiltration, vapour condensation, percolation of irrigation waters; (decrement): consumption of ground waters in evaporation and plant transpiration (U metres per day); underground inflow from neighbouring territories to the given area (Q_1 m^3 per day); underground backflow from the boundaries of the given area (Q_2 m^3 per day). The algebraic sum of these elements is equal to the changes in free ground water reserves for one day and is expressed by the value $\frac{\mu \Delta H}{\Delta t}$ metres per day, where μ is equal to the water yield of the aquifers when its level declines or to the saturation deficit of the rock when there is a rise in level; ΔH is equal to the variations in the level of the water table in metres for Δt (per day).

By denoting the area of the water balance plot as ω m^2 and bearing in mind the above-stated relations of the units of measurements, we arrive at an equation, representing the balance of ground waters, which takes the following form:

$$\frac{\mu \Delta H}{\Delta t} = \frac{Q_1 - Q_2}{\omega} + W_1 - U \qquad (1)$$

The algebraic sum of values representing the positive and negative recharge of free ground waters for one time unit is often designated by w.

In consideration of this, the equation (1) may be rewritten in the form of:

$$\frac{\mu \Delta H}{\Delta t} = \frac{Q_1 - Q_2}{\omega} + w \qquad (2)$$

When examining a plane flow of free ground waters the values of unit discharges q and q_2, applied to the unit of width of the flow should be adopted in place of water discharges Q_1 and Q_2. Instead of the area of the balance plot ω, it is sufficient in this case to take into account the extent of the chosen element of the free ground water flow Δx.

On the basis of this, the equation (2) can be rewritten in the following manner:

$$\mu \frac{\Delta H}{\Delta t} = \frac{\Delta q}{\Delta x} + w, \qquad (3)$$

where

$$\Delta q = q_1 - q_2$$

C) RELATIONSHIP BETWEEN ELEMENTS OF THE PHREATIC WATER INVENTORY AND METEORIC FACTORS

The equation for the inventory stated above reflects the direct relation between the regime (fluctuation in the level ΔH) of free ground waters and the elements of the inventory. By taking these equations as a basis and with an advance knowledge of the changes in the value of individual elements of the balance, it is possible to compute the forthcoming rise or fall in the level of the water table.

Elements of the balance of free ground waters are directly related to meteorological factors.

The value of recharge of free ground waters may be expressed by the following equation:

$$W = N - V + K + \frac{P_1 - P_2}{\omega} - (D_1 + D_2), \qquad (4)$$

where N = quantity of precipitation;

V = total evaporation from the ground surface;

K = condensation of vapours on the ground and in the zone of aeration;

P_1, P_2 = inflow and outflow of surface waters in the given area in volumetric units of measurement;

D_1, D_2 = increase in water reserves on the ground and in the zone of aeration (in case of a decline in reserves the values D_1 and D_2 become negative);

ω = area of the inventory region.

D) INVESTIGATIONS OF THE REGIME OF FREE GROUND WATERS AND THE DETERMINATION OF THEIR BALANCE ON THE BASIS OF AN ANALYSIS OF FLUCTUATIONS OF THE WATER TABLE

Using the equations of water balance as a basis, a number of investigators in their practical work (M. A. Shmidt, M. M. Krylov, A. F. Slyadnev and others) have more precisely determined these equations for the purposes of irrigation. These authors, however, have taken account only of the mean values of individual elements of the water

balance and hydrogeological environment as a whole. Accordingly, they regard variations in the level of the water table ΔH as the average for the entire inventory region. They assume that recharge of phreatic flow, accomplished by percolation of precipitation, may be determined solely according to the rise of ground water level during the annual rainy season, assuming equal values for underground inflow and outflow. But it is also just as evident that fluctuations in the water table are linked with the differences of underground inflow and outflow.

The same authors fail to make use of very valuable data pertaining to level fluctuations of ground waters to determine evaporation losses and recharge through irrigation and leakage from irrigation ditches.

From the hydrogeological point of view the best approach to a phreatic inventory should be a hydrodynamic analysis of observed fluctuations in the level of the waters, based on the non-equilibrium formulae of finite differences for underground flow (as proposed by G. N. Kamensky in 1940).

In substance, the analysis of the regime of free ground waters in a given area consists of a quantitative determination of the elements of phreatic recharge and consumption; this is done on the basis of diagrams showing level fluctuations of the water table and by means of the solution of the equations for unsteady flow in finite differences. This analysis should of course be supplemented by tests and experimental determinations of individual elements of the balance conducted at typical inventory sites (evaporation from the ground surface and from the horizon of the ground water table, variations in moisture content in the zone of aeration, observations regarding percolation of irrigation waters and precipitates with the aid of the lysimeter, etc.).

To investigate the balance of free ground waters under conditions of *plane flow* (parallel streams in plan) a minimum of three observation wells are required, distributed along the line of ground water flow and sunk to the watertight bed. These observation lines should be located only after preliminary prospecting of the ground water flow has been completed and maps with contours of the

water tablo covering a more extensive area have been compiled.

The distance between wells should be at least several hundred metres, so that the difference between absolute marks of static water levels at adjacent points should be not less than 0.20-0.50 metres.

Being in possession of water level data in three observation wells for an average moment of the given time interval (denoted by $s+1$), as well as the level of ground waters in the middle well n at the initial (s) and ultimate ($s+2$) moment of the same time interval, it is possible to calculate the value of infiltration recharge w on the basis of equations of variable flow in finite differences as proposed by Kamensky:

a) with a horizontal-impervious, or water-tight bed:

$$w = \mu \frac{h_{n,\,s+2} - h_{n,\,s}}{\Delta t} -$$

$$\frac{k}{l_{n-1,n} + l_{n,n+1}} \left(\frac{h^2_{n-1,\,s+1} - h^2_{n,\,s+1}}{l_{n-1,n}} - \frac{h^2_{n,\,s+1} - h^2_{n+1,\,s+1}}{l_{n,n+1}} \right) \quad (5)$$

In this equation the following designations are adopted:

$h_{n,\,s+2}$ = the saturated thickness of the aquifer flow, measured down to the water-tight bed in the middle well (n) at the ultimate moment of the time interval ($s+2$) in metres (Fig. 41);

$h_{n,s}$ = the saturated thickness of the aquifer flow in the same well at the initial moment (s) of the time interval Δt in metres;

k = coefficient of filtration for water-bearing rock in metres per day;

$l_{n-1,n}$ = the distance in metres from the upper well (the first along the flow) ($n-1$) to the middle bore (n);

$l_{n,n+1}$ = the distance in metres from the middle well (n) to the lower well ($n+1$) (the last along the flow);

$h_{n-1,\,s+1}$ = the saturated thickness, in metres, of aquifer flow in the upper well ($n-1$) measured from the water-tight bed to the water table at the average ($s+1$) moment of the time interval;

$h_{n,\,s+1}$ = the same for the middle well (n);

$h_{n+1,s+1}$, = the same for the lower well ($n+1$):

Δt = the time interval in days between two chosen moments of observation (s and $s+2$).

The value of w is expressed in metres per day, but to place it against the amount of precipitates it will be more convenient to change it to millimetres per day by multiplying it by 1,000.

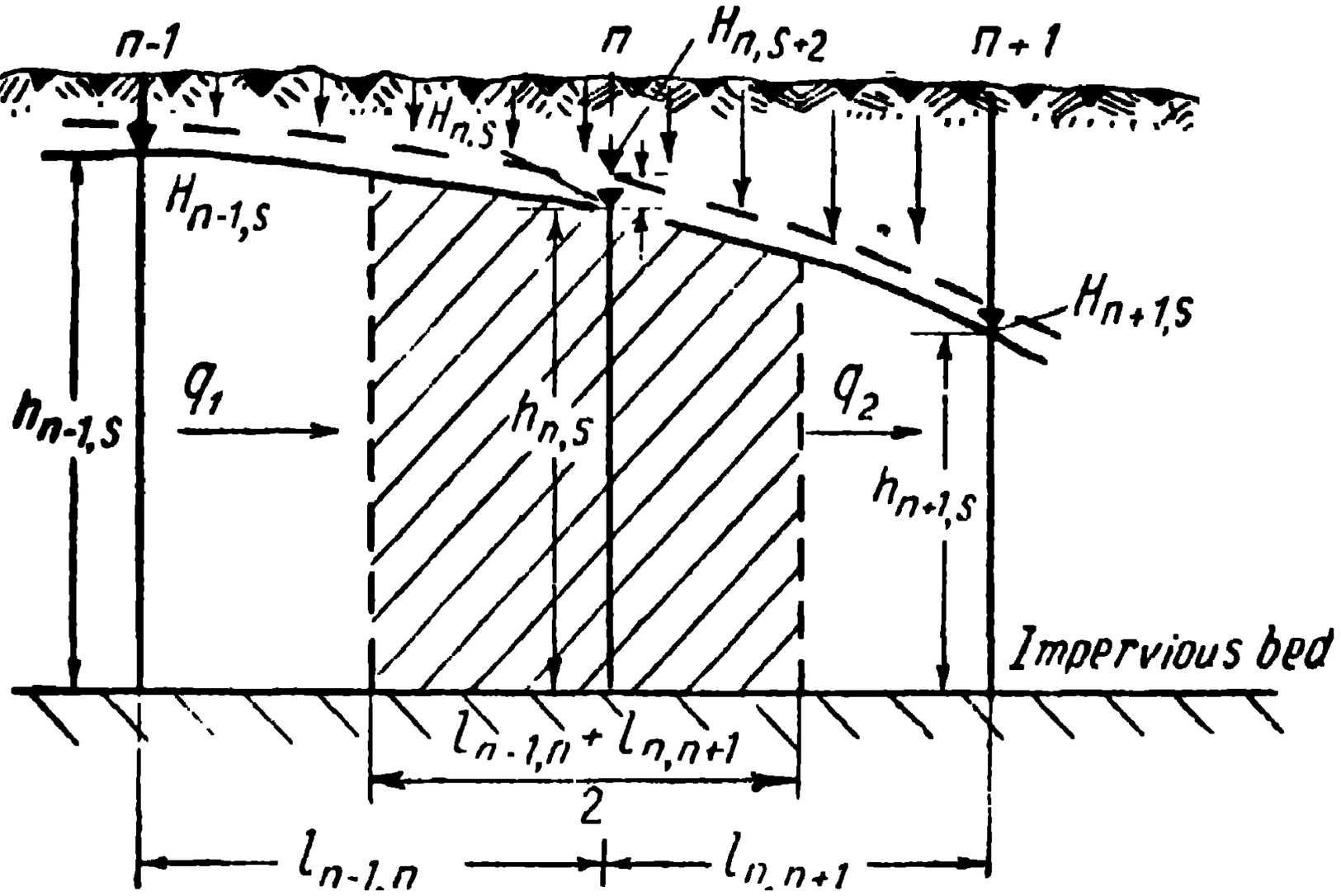

Fig. 41. Element of ground water flow with a horizontal impervious bed.

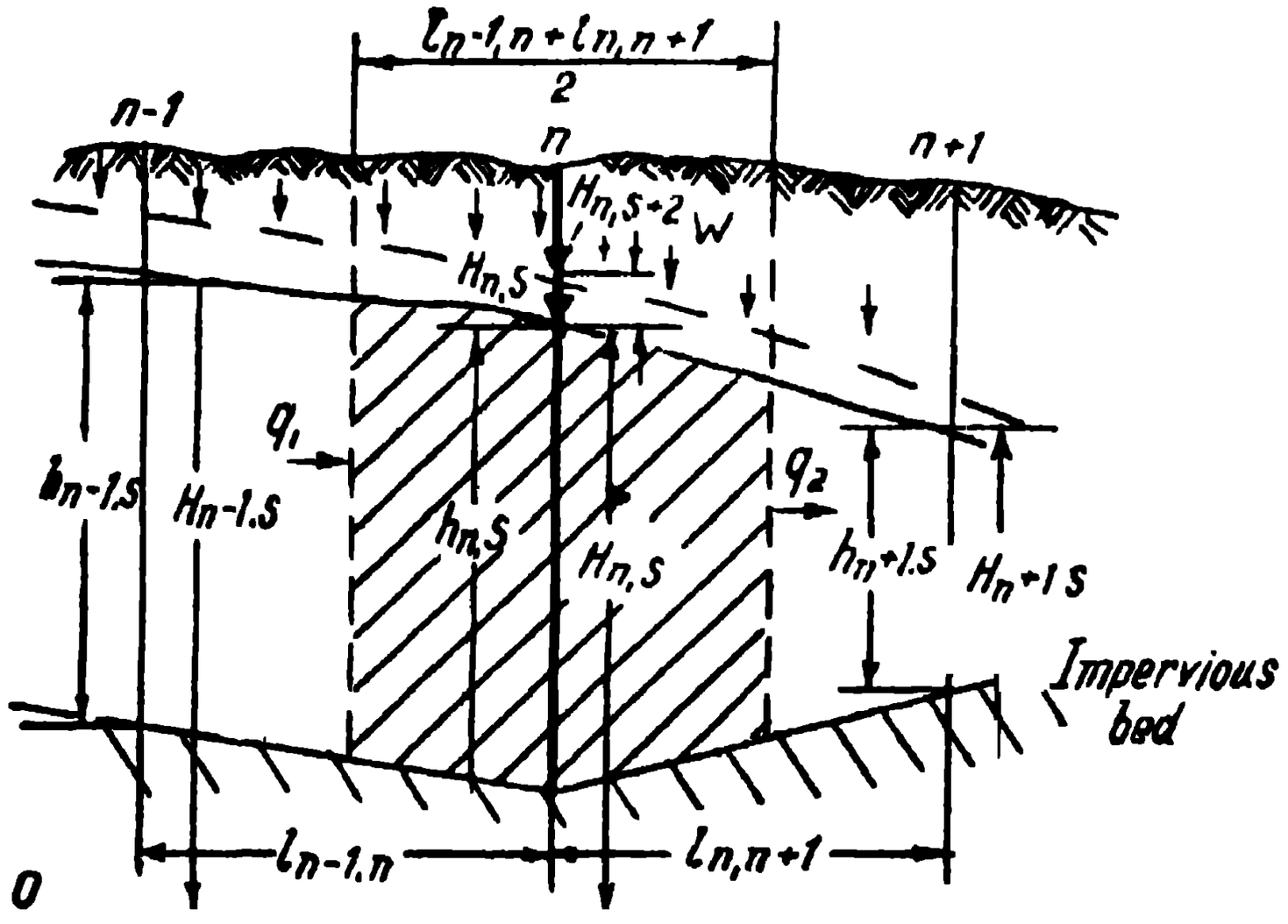

Fig. 42. **Element of ground water flow with a sloping impervious bed.**

b) with a sloping water-tight bed:

$$w = -\mu \frac{H_{n,s+2} - H_{n,s}}{\Delta t} - \frac{2k}{l_{n-1,n} + l_{n,n+1}} \left(\frac{h_{n-1,s+1} + h_{n,s+1}}{2} \times \right.$$

$$\left. \times \frac{H_{n-1,s+1} - H_{n,s+1}}{l_{n-1,n}} - \frac{h_{n,s+1} + h_{n+1,s+1}}{2} \times \frac{H_{n,s+1} - H_{n+1,s+1}}{l_{n,n+1}} \right) \quad (6)$$

where $H_{n-1,s+1}$, $H_{n,s+1}$, $H_{n+1,s+1}$ = level of ground water table at the average moment $(s+1)$ in the wells $n-1$, n and $n+1$ for the given time interval (Fig.42).

$H_{n,s+2}$ = level of the ground water table in the well n at the ultimate moment $(s+2)$.

The other designations remain the same.

The more usual case of *radial flow* (Fig. 43) requires preliminary prospecting by means of several boreholes, a necessary procedure for the compilation of a contour map of the water table. Having found the direction of flow, a line of three observation wells ($n-1$, n and $n+1$) is made. In this case the side (flanking) wells more precisely determine the width of flow.

On the contour map the direction of flow is plotted perpendicularly to the contour lines.

The cross-section of flow is represented by the area of vertical planes passing along the contour lines and limited by two selected lines of flow and the impermeable bed. The width of the upper cross-section of the flow between the selected water currents is equal to the distance along the water contour passing through the wells $n-1$, $m-e$, b_{n+1}. Correspondingly, the width of the mid-cross-section passing through the well n is equal to b_n, while that of the lower $n+1$ is equal to b_{n+1}.

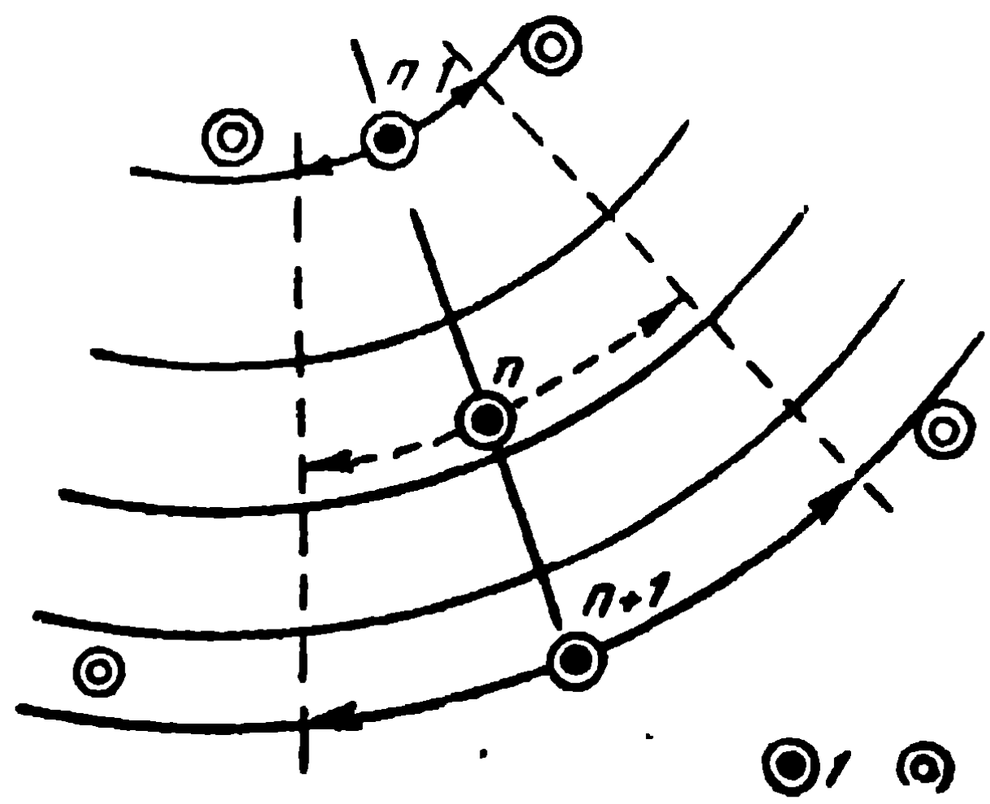

Fig. 43. Radial-divergent flow of ground water.

1—observation wells of main line; *2*—supplementary wells.

Calculations of w in a radial flow with a sloping impervious bed are effected on the basis of equation (7). If there is a horizontal impervious bed this equation is simplified, for the values H and h, when written with similar indices, are equal to each other (for example, $H_{n-1,\,s+1} = h_{n-1,\,s+1}$).

$$w = \mu \frac{H_{n,s+2} - H_{n,s}}{\Delta t} - \frac{4K}{(b_{n-1} + 2b_n + b_{n+1})(l_{n-1,\,n} + l_{n,n+1})} \left[\left(b_{n-1} h_{n-1,\,s+1} + b_n h_{n,\,s+1} \right) \frac{H_{n-1,\,s+1} - H_{n,s+1}}{l_{n-1,n}} - \left(b_n h_{n,\,s+1} + b_{n+1} h_{n+1,\,s+1} \right) \frac{H_{n,\,s+1} H_{n+1,\,s+1}}{l_{n,n+1}} \right]. \quad (7)$$

Letter designations here are the same as before.

In making computations, the curve illustrating level variations should be split into elementary sections, on each of which the water level gradually rises or falls. Time intervals thus selected are usually characterized by stability of active meteorological factors (melting of snow, precipitation, droughts) or correspond to certain moments of the irrigation cycle (watering, closing down of the irrigation system, winter washings, etc.).

With the foregoing equations as a basis and having calculated the value of seepage of free ground waters w for the first space of time, analogous computations for the next period are then made, etc.

Positive values for w determined by calculations will point to the predominance of seepage over evaporation, while negative values of w will testify to the contrary.

Table 8 is an example of calculations of recharge of ground water according to formula (5).

It is seen from the foregoing that to calculate the value for ground water recharge, the coefficient of filtration of water-bearing rocks (K) should be known as well as the value μ (water release, or the saturation deficit of the rock prior to its complete saturation within the belt of fluctuation of the water table).

Table 8

Computation of Free Ground Water Recharge (w) According to Equation (5) for a Section of an Observation Line of Three Boreholes

Date	Thickness of ground water flow in metres			Δt days	$h_{n,s+2} - h_{n,s}$ (metres)	μ	w mm. per day
	Boring 1	Boring 2	Boring 3				
	$h_{n-1,s+1}$	$h_{n,s+1}$	$h_{n+1,s+1}$				
4/III-1948							
1/IV	27.63	26.88	24.05	28	—0.04	0.12	—0.03
16/IV	27.97	27.07	24.77	15	+0.43	0.10	+2.94
25/IV	28.34	27.35	25.07	9	+0.12	"	+1.38
19/V	28.29	27.46	24.65	24	+0.09	"	+0.50
1/VIII	27.96	27.38	24.54	74	—0.24	"	—0.14
1/X	27.57	27.17	24.30	61	—0.26	"	—0.21
28/XI	27.39	26.91	24.12	58	—0.18	"	—0.10
2/I-1949	27.32	26.79	24.00	35	—0.07	"	—0.01
28/II	27.24	26.69	23.91	57	—0.12	0.09	0

Notes:

1. A uniform stratum structure with a filtration coefficient of 8.83 metres per day is assumed;
2. Level mark of impervious bed—121.00 metres;
3. Distance between borewells 1 and 2—$l_{n-1,n}$=830 metres; and between borewells 2 and 3=$l_{n,n+1}$=1,630 metres.

The first of these values is ascertained either on the basis of test pumpings or from laboratory determinations of the coefficient of filtration for each individual layer, the latter being less precise.

The value of μ is determined on the basis of moisture content and porosity of the ground in the belt of water table fluctuations during various periods of the year.

The inflow of free ground waters towards the selected element of flow is determined on the basis of the following formulae:

a) with a plane flow and horizontal impervious bed:

$$q = K \frac{h^2_{n-1,s+1} - h^2_{n,s+1}}{2l_{n-1,n}}; \quad (8)$$

b) with a plane flow and a sloping impervious bed:

$$q = K \frac{h_{n-1,\,s+1} + h_{n,\,s+1}}{2} \cdot \frac{H_{n-1,\,s+1} - H_{n,\,s+1}}{l_{n-1,n}}; \qquad (9)$$

c) with a radial flow:

$$Q = K \frac{b_{n-1} \cdot h_{n-1,\,s+1} + b_n \cdot h_{n,\,s+1}}{2} \cdot \frac{H_{n-1,\,s+1} - H_{n,\,s+1}}{l_{n-1,n}}. \qquad (10)$$

The designations are the same as before.

Outflow of free ground waters from the given element of the flow is computed by the same formulae, but in place

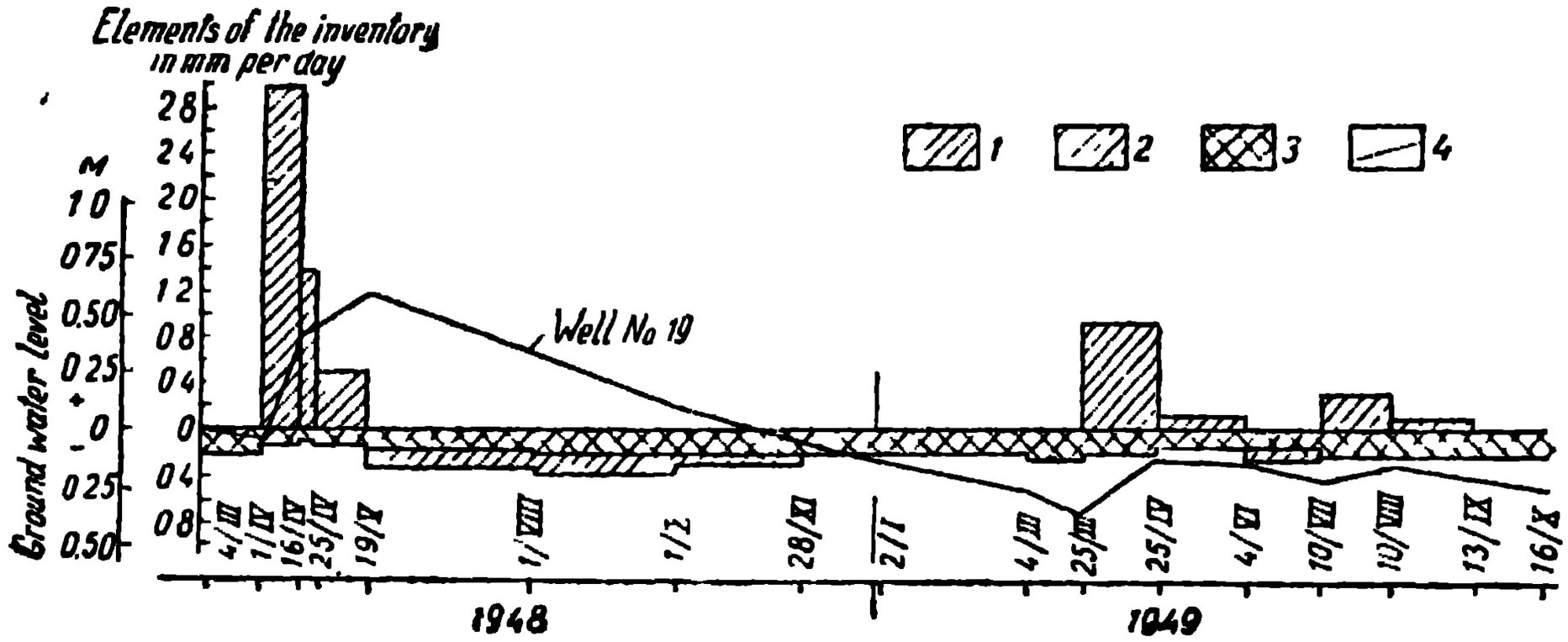

Fig. 44. Element graph of a ground water inventory.

1—infiltration of atmospheric precipitates; *2*—evaporation of ground water; *3*—difference between lateral inflow and outflow of ground water; *4*—ground water level fluctuations.

of the thicknesses of the flow in the upper and middle cross-sections ($h_{n-1,\,s+1}$ and $h_{n,s+1}$), corresponding thicknesses of flow in the middle and lower cross-sections ($h_{n,\,s+1}$ and $h_{n+1,\,s+1}$) are taken.

Having determined the elements of water balance $\left(w, \frac{\Delta q}{\Delta x}\right)$ for individual time intervals at the selected elementary section, their total values for the entire annual period may be easily computed.

An example of a water inventory for an area which had been subject to observations of water level fluctuations during 1948-1949 is shown in Table 9 and represented graphically in Fig. 44.

As may be seen, seepage ceased by the 19th of May and

comprised 68.5 mm. Up to this time the expenditure of ground water proceeded solely through underflow. The latter was less abundant than seepage, and up to the 19th of May the ground water balance was positive and the ground water level rose.

From the 19th of May evaporation of ground water increased and this continued till the 28th of November; together with the uninterrupted outflow it exceeded spring phreatic accumulation, with the result that by the end of the year the inventory became negative (—26.8 millimetres).

The total value of ground water evaporation together with transpiration comprised 30.3 millimetres per annum or 44% of infiltration. Because the total outflow into the river (beyond the boundaries of the area under study) reached 65.0 millimetres (95% of infiltration), its compensation, apart from percolation (68.5—30.3 = 38.2), required extraction from primary phreatic sources which equalled 26.8 millimetres of the water layer.

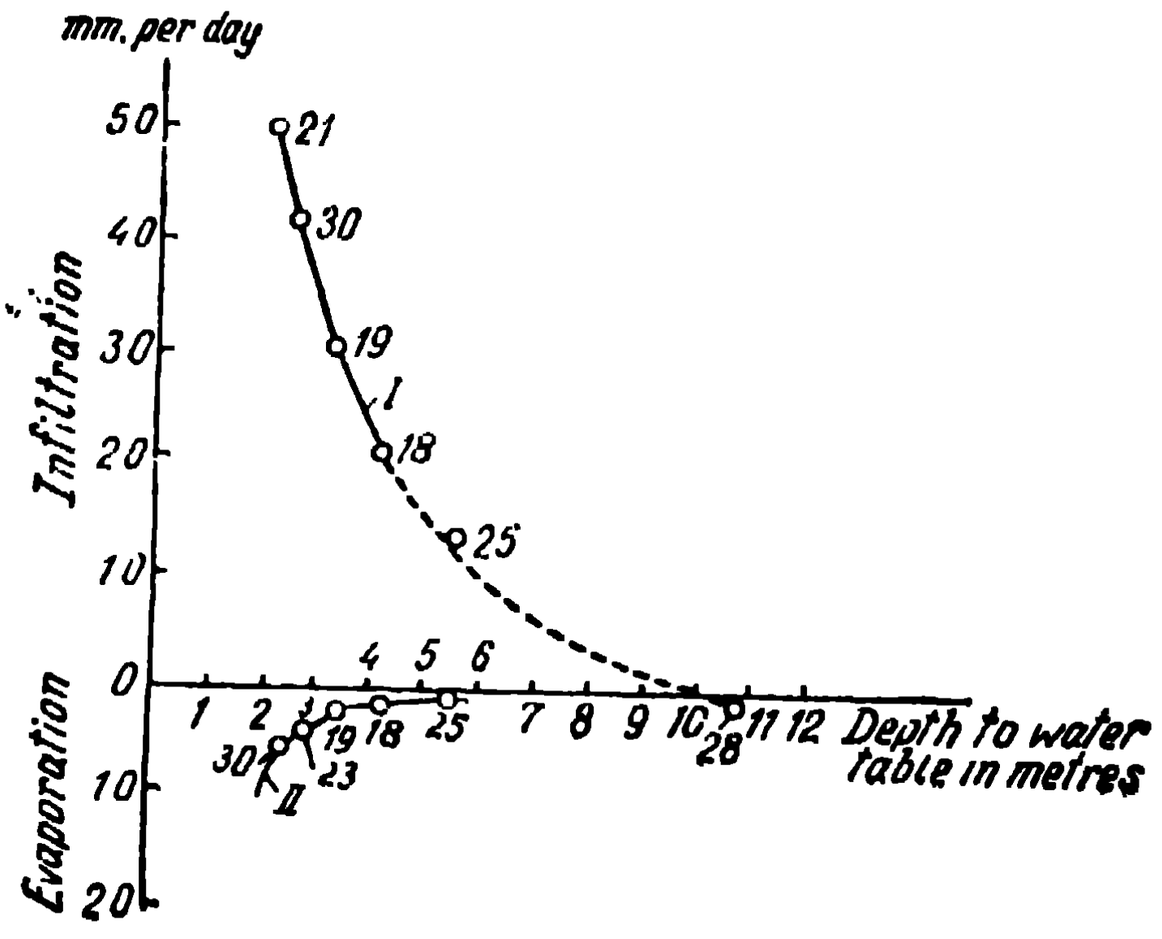

Fig 45. Relation curves: precipitation infiltration and the depth of the free ground water table for the spring period of 1/IV-16/IV 1948 and evaporation for the period of 19/V-1/VIII 1949.

Thus, the inventory clarified the questions of development of seasonal fluctuations in ground water level, of sources of underflow and of the role of recharge and evaporation in the ground water balance.

Elementary inventory plots should be representative for any given territory and determined on the basis of pertinent data obtained from hydrogeological investigations.

Upon completion of the water inventory at elementary balance plots and the investigation of the relation between individual balance elements and active natural and arti-

Table 9

Balance of Free Ground Waters

Date	Time interval Δt (days)	Inflow q_1 in m³ per day	Flow-out q_2 in m³ per day	Increment (+) or loss (−) Δq in m³ per day	Increment (+) or loss (−) $1{,}000\frac{\Delta q}{\Delta x}$ in mm. per day	Recharge w in mm. per day	Increment during the time Δt through:		Decrement during the time Δt through:		Balance (mm.)
							lateral inflow minus flow-out $\frac{\Delta q}{\Delta x}\Delta t$ (mm.)	infiltration $w\Delta t$ (mm.)	lateral flow-out minus inflow $\frac{\Delta q}{\Delta x}\Delta t$ (mm.)	evaporation $w\Delta t$ (mm.)	
4/III-1948	28	0.220	0.390	−0.170	−0.14	0.03	—	—	3.9	0.9	−4.8
1/IV	15	0.260	0.323	−0.083	−0.07	+2.94	—	44.1	1.1	—	+43.0
16/IV	9	0.294	0.323	−0.029	−0.05	+1.38	—	12.4	0.5	—	+11.9
25/IV	24	0.246	0.398	−0.152	−0.12	+0.50	—	12.0	2.9	—	+9.1
19/V	74	0.172	0.398	−0.226	−0.18	−0.14	—	—	13.3	10.4	−23.7
1/VIII	61	0.128	0.394	−0.266	−0.22	−0.21	—	—	13.4	12.8	−26.2
1/X	58	0.137	0.389	−0.252	−0.21	−0.10	—	—	12.2	5.8	−18.0
28/XI	35	0.155	0.385	−0.230	−0.19	−0.01	—	—	6.7	0.4	−7.1
2/I−1949	61	0.159	0.380	−0.221	−0.18	0	—	—	11.0	—	−11.0
Total for the year in millimetres and % of infiltration							$\frac{+68.5}{100}$	$\frac{-65.0}{95}$	$\frac{-30.3}{44}$	$\frac{-26.8}{39}$	

Note: **Length of the element of flow Δx=1,230 metres**

ficial factors, the obtained information should be extended to territory with analogous conditions.

Other factors being equal (lithology of water-bearing rock, drainage and recharge of free ground waters), a very close relation can be found between infiltration and the depth of the water occurrence (Fig. 45).

In irrigated regions the relation between percolation of irrigation waters and irrigation rates may thus be investigated and a forecast made of variations in the phreatic water regime in case of a change in irrigation schedules.

Having determined the difference between inflow and outflow of free ground waters within the boundaries of each balance plot, i.e., the value $\Sigma\frac{\Delta q}{\Delta x}\cdot\Delta t$, it becomes possible to apply this value to territories possessing similar hydrogeological conditions and compute the mean value for the territory as a whole.

If there is no recharge by underflow into the given region (under conditions of a surface watershed and when the boundaries of the balance plot coincide with the line of the free ground water divide, or if there is phreatic underflow in the irrigated area), the value $\Sigma\frac{\Delta q}{\Delta x}\cdot\Delta t$ multiplied by the area represents the underflow from this region. The ratio of the value of this underflow to the area, as expressed in litres per second from 1km², is equal to the modulus of underflow.

By using the modulus of underflow of the underground catchment area F, the dynamic sources of free ground waters may be determined, equal to:

$$Q=86.4M\cdot F,$$

where Q=discharge in m³ per day of the flow through a cross-section normal to water current lines;

M=modulus of underflow in litres per second from 1 km² of the area;

F=underground catchment area (km²).

Average dynamic reserves of free ground waters for many years running may be determined by multiplying the aver-

age amount of recharge water for a long-term period (w) by the area where this recharge is taking place.

Contours of the catchment area and water table should be shown on the hydrogeological map.

E) STUDY METHODS OF INDIVIDUAL ELEMENTS OF WATER BALANCE AND THEIR USE IN THE GROUND WATER INVENTORY

1) Atmospheric Precipitates

Measurements of precipitation are conducted by meteorological stations, but in their absence and if the given territory is large, a special network of meteorological posts should be set up whose duties include precipitation observations.

Liquid and solid precipitates are recorded by rain-gauges installed, according to the instructions of the Hydrometeorological Service, at a height of two metres. These rules should be followed in order to obtain comparable data at all new posts.

Experience has shown that such rain-gauge readings frequently differ from precipitation measurements at ground level. Therefore, for more precise recordings of precipitates reaching the ground it is recommended to install additional rain-gauges at ground level at water balance sites. Such differences are particularly noted in forests and forest belts, where the placing of extra rain-gauges is therefore obligatory.

It is very important to make a special recording of variations in the elements of microclimate depending upon topographic height. In mountain and submountain regions a number of meteorological posts should be provided at various altitudes.

Prior to the water inventory in such regions the Hydrometeorological Service should be requested for additional meteorological data in order to obtain a more detailed understanding of meteorological conditions.

If the Hydrometeorological Service cannot organize a permanent observation network, a temporary set of posts should at least be arranged.

Apart from the use of rain-gauges, solid precipitates are

recorded during the winter by special levelling rods placed at meteorological sites.

Snow surveys should also be carried out every ten days (or episodically) enabling conclusions to be drawn, according to local topography, of the snow cover over large areas.

Snow surveys clarify such questions as condition, depth, and degree of compactness of the snow cover, and the condition of the underlying soil. From this the water layer (in millimetres), equivalent to the given snow cover, may be computed.

Snow readings just prior to the melting period are especially significant in revealing a very important element of water balance, viz., water resources in the solid phase at the end of the inventory year.

Methods of studying precipitates are explained in manuals issued in 1936 and 1940 for the use of meteorological stations of the Hydrometeorological Service of the U.S.S.R.

2) Evaporation

Evaporation is classified as from open water surfaces (V^b), from soil surfaces (V^n), from the horizon of free ground waters (U) and, lastly, from vegetation transpiration (V^t). Evaporation of free ground water leads principally to moisture enrichment of the zone of aeration, while the others contribute to a rise of atmospheric moisture.

Studies of open water evaporation have for their aim the obtaining of quantitative characteristics needed for the solution of the equation of water balance and the establishment of a correlation between this and other types of evaporation.

Although the question of evaporation processes is a very old one, there are up to the present no universally accepted and satisfactory methods for its study nor adequate equipment to carry out surveys.

Available measuring instruments do not allow direct observation of actual evaporation because of the very complicated relationship of this process with the whole complex of factors (air humidity, wind, radiation, surface unevenness, etc.). Evaporation from water surfaces may be determined by a floating evaporator designed by the Hydrogeo-

logical Institute. The site for this evaporator should be selected to satisfy average conditions existing in the given water basin—temperature of upper water layer, temperature and humidity of the air, and velocity of the wind.

B. V. Polyakov has offered the following equation for calculating the total monthly evaporation from the surface of a river basin:

$$V = aZ + bt^n + N(1-\eta), \qquad (11)$$

where V=evaporation during the given period;

Z=moisture content of the upper one-metre layer of the soil (millimetres);

t=average monthly air temperature (degrees);

N=precipitates during the period (millimetres);

η=coefficient of run-off;

a, b, n=numerical indices.

Polyakov has compiled corresponding diagrams to facilitate calculations.

Total evaporation from the surface of a river basin V may also be defined on the basis of a formula proposed by P. S. Kuzin:

$$V = a \cdot N_o^2 \cdot d_o \qquad (12)$$

where V=total annual evaporation from the river basin (mm.);

N_o=rate of precipitation (mm.);

d_o=rate of moisture deficit (mm.);

a=a coefficient equal to:

0.000477-0.000494 for the Donets Coal Basin,

0.000549-0.000579 for the Ukraine,

0.000628-0.000654 for the Transvolga Region.

To compute the total evaporation during any month the same author has compiled special diagrams showing the relation of evaporation losses against the average monthly temperature of the air. These diagrams satisfy the usual conditions of a year of average rainfall and are applicable to regions with sufficient precipitation.

The most widely used experimental methods of evaporation study from soil surfaces are based on systematic study of variations in the weights of soil monoliths.

Among prescribed evaporators, mention may be made of designs by Rikachev, Popov, new GGI-500 types designed by the State Hydrological Institute, and the GGI-51 hydraulic soil evaporator.

Rikachev's evaporator consists of a 40×25×30 cm. metal box into which a soil monolith is placed and which, after weighing, is put into a second somewhat larger box. This is placed in a pit, even with the ground. Upon expiration of observation time the inner box is again weighed.

This type has its negative side: the soil monolith is completely isolated from the surrounding soil. Compared to this latter, the soil sample desiccates in dry weather, while in wet it becomes oversaturated.

A somewhat better model is the evaporator-lysimeter devised by Popov, a description of which is given in the above-named manual for meteorological stations.

I. S. Vasiliev who made a comparative study of evaporation with the aid of the evaporators cited above, has published (1950) the following appraisal of their operation.

In Popov's design an incomplete capillary closure between the monolith and natural soil is observed which exercises a negative influence over the rising or descending flow of soil moisture. During heavy rainfall, soil particles are washed from the monolith to the water-collecting vessel.

In the evaporator proposed by Rikachev the solid bottom excludes any communication between the moisture in the monolith and that in the surrounding soil.

Therefore, neither type can give true evaporation values (measurement errors fluctuate within considerable limits, but do not exceed ±10% for the final figures).

In the opinion of Vasiliev, Popov's evaporator-lysimeter No. 5 has very little advantage over the one proposed by Rikachev.

The GGI-500 soil evaporator of the State Hydrological Institute is manufactured for the Hydrometeorological Service. A complete set includes two evaporators and one rain-gauge. Other accessories needed for work with this evaporator are 150-kilogram scales and weights of various size.

The evaporator is composed of two cylinders, one freely moving within the other, and a funnel-shaped vessel for

collecting water percolating through the monolith. The latter is placed within the inner cylinder.

The inner cylinder with the monolith is regularly weighed at 7 a. m. and 9 p. m.

A more reliable model, the small GGI-51 hydraulic soil evaporator designed by V. A. Urivaev and P. N. Burtsev and made by the State Hydrological Institute has found wide use lately. Its description, as well as that of the preceding one, are given in the aforementioned Hydrometeorological Service manual.

The principal difference of this evaporator (as compared to the GGI-500 type) is: weighing is substituted by very reliable observations of the vertical displacement of the monolith, which is enclosed in a water-tight container and suspended in water (for which a water basin is provided). The vertical travel of the monolith corresponds to certain predetermined values in weight which the monolith loses or gains in accordance with either evaporation of water or the addition of precipitation.

Besides the methods used for determining soil evaporation as discussed above, there are other methods of study based on changes of moisture content in a column of soil-ground.

Evaporation of free ground waters is determined with the aid of an "underground" rain-gauge or lysimeter.

For a shallow level of phreatic water use may be made of a lysimeter installation similar to one proposed by A. A. Rodet in 1938 but somewhat modified by the author (Fig.46).

A soil monolith 80-100 centimetres high is cut from the soil or underlying ground and placed in a water-tight box *1* provided with a bottom and with a side pipe *4* in its lower part. The pipe is 1.5 metre long and 3/4"in diameter. Prior to placing the monolith, the bottom of the box is covered with 20 centimetres of gravel or coarse sand.

The branch pipe in the box is terminated by a wire gauze twisted into a roll *3* which serves for communication between the water in the monolith and the pipe. The layer of gravel or sand must completely cover the wire gauze roll.

The box with the soil sample is placed in a trench so that the upper edge is even with, or 3 or 4 cm. higher than, the surface of the ground. The other end of the pipe *4* is

made to enter the observation chamber, a timbered pit with a roof and specially constructed entrance. After placing the monolith the trench is backfilled with extracted ground.

In the observation pit the end of the branch pipe is joined to a T-piece *5* to which a glass piezometer *7*, fixed on a stand, is connected. The other opening of the T-piece is connected, by means of a rubber tube *b*, to a funnel *a* fixed on the stand *8*. Two 7-8 mm. pipes pass through the bottom of the funnel;

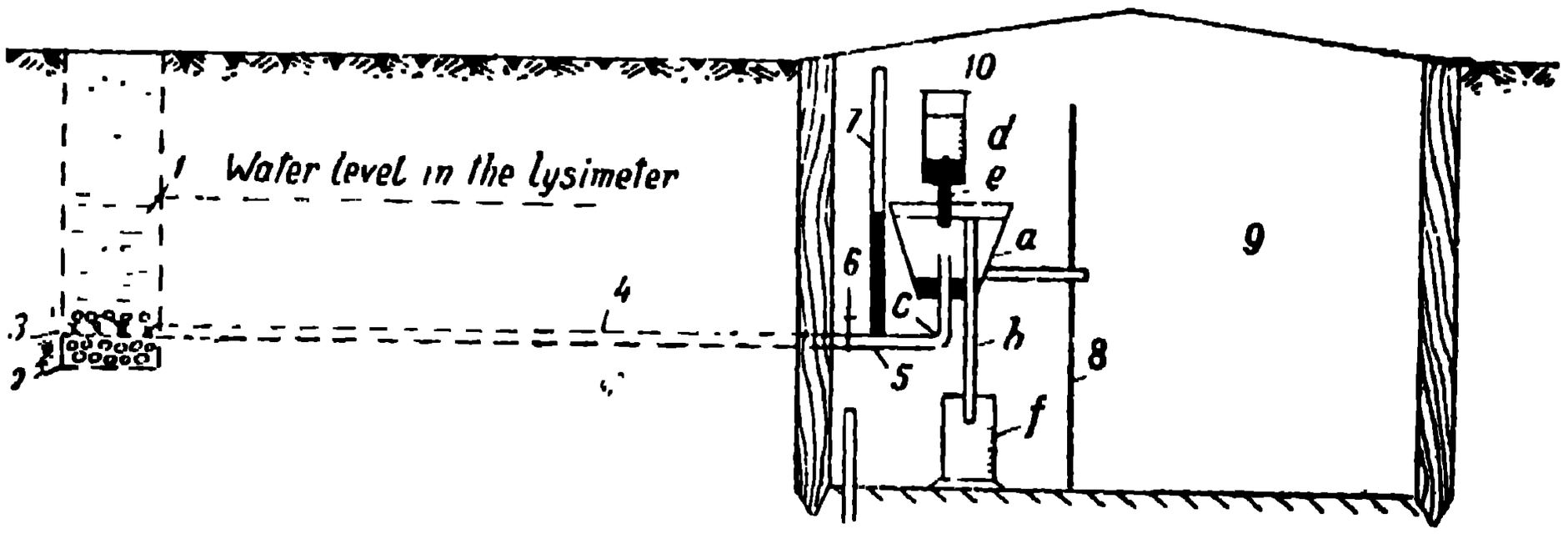

Fig 16. Lysimeter installation.

1—lysimeter filled with sand; *2*—gravel; *3*—screen; *4*—water outlet pipe, *5*—tee-piece; *6*—valve (cock); *7*—piezometer; *8*—stand; *9*—pit; *10*—measuring equipment.

one pipe is connected with a rubber tube *b* coming from the lysimeter, while the other *c* serves as an outlet for surplus water from the funnel *a* into the measuring cylinder. A Mariotte vessel, secured above the funnel, serves as a measuring cylinder *e* with a discharge pipe *d*.

After placing the monolith in the water-tight box the latter is charged with water from below until complete saturation of the monolith is achieved; this may be done before connecting the box to the measuring apparatus, for which the only thing needed is a special cock *6* near the T-piece *5*.

If this cock be opened then, according to the law of communicating vessels, the water in the monolith and in the funnel *a*will assume the same level. The pipe *d* from the Mariotte vessel should be placed so that its end is 3-4 mm. below the end of the discharge pipe *c*. After establishment of equal levels in the monolith and funnel, the flow from the

latter will cease and there will be no delivery of water from the Mariotte vessel.

As a result of evaporation from the horizon of water contained in the monolith, the level in the funnel *a* will begin to fall. A level drop of 1-3 mm. is easily recorded with the piezometer. Knowing the water yield of the rock in the box, there will be no difficulty in calculating the layer of evaporated water. Thus, if the water yield of the ground constitutes 0.10 and the falling level recorded by the piezometer is equal to 2 mm., then the layer of water evaporated, without consideration of the water level drop in the funnel, will be equal to $2 \times 0.1 = 0.2$ mm.

But since with a decline of water level in the lysimeter (due to evaporation from the monolith) the water level in the funnel (according to the law of communicating vessels) will also begin to drop, evaporation will be equal to the sum of water losses from the monolith and the water discharge from the funnel.

Precipitation and subsequent percolation will cause the water level to rise in the monolith. This rise will be easily recorded by the piezometer within limits of 2-3 mm.; computation of accumulated water will be the same as for evaporation.

If precipitation is large, a flow of percolated water through the funnel into the lower measuring vessel will be noticeable. In case of considerable evaporation, the Mariotte vessel *e* will begin to operate and admit a corresponding quantity of water into the funnel.

In the latter instance the rate of flow from the monolith, funnel (according to the piezometer), and Mariotte vessel should be taken into account.

The water table in the monolith will keep its same level for a long time and permit its comparison with the natural phreatic level when this is not deep. The height of the monolith block should be somewhat greater than the maximum capillary rise (lift).

For studying evaporation from a water table occurring at depths far in excess of those for which recordings may be made with the aid of the lysimeters described above, underground lysimeters are used whose design is similar to the aforementioned.

It should be noted that data obtained with the aid of evaporators is valid only for the points of their installation and for the selected conditions of underground water occurrence, as well as for a definite structure of the zone of aeration. Therefore, the direct use of this data for a water inventory is possible only in limited areas. To extend the results of such observations to larger territory, it will be necessary to examine the relation of evaporation losses thus obtained with other factors, such as depth to the water table, lithology of the rock in the zone of aeration, chemical composition of the water, etc. It is accordingly recommended to place lysimeters at water balance sites having differing natural conditions.

3) Transpiration by Vegetation

There are many ways of studying vegetation transpiration, but there are, as yet, no universally accepted observation methods of this very essential part of the inventory. The method discussed below has been adapted from the works of M. M. Krylov, published in 1939.

The principle serving as a basis for this method has been borrowed from A. A. Nichiporovich who had made a study of water losses due to plant desiccation. Investigations have shown that during the first 10-15 minutes after a plant has been cut, its rate of water evaporation does not differ from the rate before cutting, after which transpiration ceases entirely and further losses in the plant's weight are due only to desiccation.

A cabin, sheltered from the wind and provided with technical scales, is constructed at the site intended for transpiration observations. A silk thread, attached to one of the scale pans, will serve to hold the plants.

One of the scale pans is counterbalanced with washed medium-grained sand placed into porcelain cups that have been check-weighed previously on an analytical balance.

Plants are then rapidly mowed from a selected 0.25×0.25 m. plot, gathered into a tuft, attached to the silk thread and weighed. This procedure should take no more than 20-25 seconds. The tuft is then removed and the stalks of the

plants are spread on racks. Two minutes after being cut the plants are again gathered into a tuft and weighed. The observed loss of weight is compensated for with a corresponding amount of sand added into a porcelain cup. Again the stalks of the plants are spread on the racks and four minutes later are again weighed, etc.

The sand from the porcelain cups is placed into packets and weighed. The weight of this sand will show the transpiration value during corresponding intervals of 2,4, etc. minutes.

Transpiration analyses should be conducted for an uninterrupted 24 hours, spending from 10 to 15 minutes for each bunch of plants. This applies particularly to periods before and during flowering and after ripening of the plants.

To compare transpiration intensity with the general hydrometeorological environment, it is advisable to carry out parallel observations of moisture content and temperature of the air and soil, cloud occurrence, direction and strength of the wind, as well as variations in the depth of free ground waters.

4) Condensation of Atmospheric Moisture

Poor advances have so far been made in recording the water that condenses in the air and penetrates into the pores of the ground.

Existing methods of condensation study are chiefly based upon experiments with earth monoliths placed at various depths beneath the ground and with evaporators as described above, as well as upon observations of the moisture content of the air in the soil and in the lower atmospheric layer.

In the case of cohesive or semi-cohesive earths the results of condensation may be investigated by weighing small earth monoliths. To do this a pit is dug, into the walls of which horizontal holes are drilled at various depths from the surface (approximately 0.15, 0.30, 0.50, 1.5, and 2.0 metres). Samples of rock enclosed in wire nets are inserted into these niches. Regular weighings of such monoliths on technical scales will reveal changes in weight due to the formation of condensation. Parallel observations should be

made of ground temperatures at corresponding depths by inserting soil thermometers into specially drilled holes in the pit walls. These holes should be on the same levels with the monoliths. The walls of the pit should be well shored and heat-insulated with bitumen.

Condensation of vapour in the soil air may also be observed with the aid of soil evaporators.

Any addition to the weight of a soil monolith (in the absence of precipitation) will point to an enrichment of condensation moisture. However, to definitely determine the origin of the condensed vapour in the monolith (whether from above or below), supplementary observations of vapour elasticity in the soil-air must be conducted with the aid of the Lebedev soil hydrograph; an analysis must also be made of the humidity content of the lower atmospheric layer.

Condensation from the horizon of shallow-lying phreatic waters may be easily determined by means of the already described lysimeters, placed on the ground, but beneath a glass canopy, to safeguard it against precipitation. The greatest condensation will be recorded during daylight hours and in hot weather, when the temperature difference between the surface and below ground is at its maximum.

A number of experimental condensation gauges have been designed by A. F. Slyadnev in 1941 for readings in sands. Roughly speaking, these instruments, vessels with ribbed and perforated walls, bottom and top are provided with a discharging arrangement (wick) and with a measuring vessel and electric level-gauge; this apparatus is filled with sand extracted for observation and placed at some depth under a sand ridge.

The most advanced and theoretically founded branch of moisture condensation science is the study of the thermal regime and moisture content within the zone of aeration; such surveys permit tracing changes in absolute elasticity values of vapours contained between the ground surface and the capillary zone and to establish variations in ground temperature. A necessary addition to this is the investigation of water vapour elasticity in the lower layer of the atmosphere.

5) Surface Run-Off

In the majority of cases surface run-off is the principal element of the water balance, the other factors of the balance assuming first place only in deserts and semi-deserts.

Surface inflow to a given area or region includes the volumes of rivers, springs, canals and irrigation channels conveying water to the given territory.

Quantitative recordings of run-off should be performed by a network of hydrometric (water-gauge) stations through prescribed hydrometric methods (current meters, weirs, races, floats, etc.).

Permanent hydrometric posts should be set up on all streams conveying water towards or away from the contours of a given water balance area. After each post has determined the relation between discharge and the water horizon its further activities may be limited to systematic measurements of level fluctuations for computations of discharge. To control the relationship established previously between discharge and level, periodic readings of discharge should be made.

Hydrometric posts stationed along the boundaries of the area (region) will thus be able to compute the surface run-off as related to the water inventory. Accordingly, such a hydrometric network is called a "balance network" and its observations are designated as "balance hydrometry."

Of cardinal importance in irrigated regions is the recording of irrigation waters, dates and norms of their delivery to the fields, and the amount of waste water. For this purpose the regions being dealt with are divided into subregions according to their hydromodular features, in each of which the actual watering regime is carefully recorded.

Particular pains should be taken with the water being conveyed in the main channels to the area; for this self-recording limnigraphs should be used. Similar observations, although with less exactness, should be carried out in the distribution ditches. It is absolutely essential to register the beginning and end of the irrigation cycle, the quantity of water delivered and the area irrigated, as well as the mode of irrigation. Discharge data in the channels will reveal the leakage factor in the water inventory.

Waste waters are recorded by means of hydrometric observations in drainage channels and main collectors.

It is particularly important to note the operation of collectors and spillways and check the amount of discharge against the technical condition of the drainage system. All measures pertaining to technical improvement of this system (cleaning, deepening, etc.) should also be duly registered.

A knowledge of the definite areas being irrigated during any particular watering cycle will be of no little value in revealing the phenomena underlying the phreatic water regime and in making the water inventory. This question also concerns precise determination of the coefficient of land utilization, an account of which is obligatory for an appraisal of irrigated lands.

Variations of reserves in open bodies of water (streams and basins) likewise represent an important item in the water balance, such variations requiring recording of levels and surface areas.

6) The Zone of Aeration

When investigating the zone of aeration, attention should be principally paid to determining its moisture reserves, that is, the natural moisture content from the surface of the ground to the water table.

Studies of moisture content dynamics in the zone of aeration made by M. M. Krylov in 1939 and A. V. Lebedev in 1951 have proven that this zone is extremely heterogeneous in this respect. From the ground down to a certain depth (0.9-1.5 metres, depending upon climate and lithology of the rock) there is a most variable moisture belt; below this, down to the capillary fringe, there is a belt of relatively constant moisture, while still down further lies the capillary zone itself.

One of the main tasks in the study of the zone of aeration is to obtain a full understanding of the regime and dynamics of moisture migration within the above-stated belts—items of considerable interest for future anticipation of their moisture content.

Sinking of pits is the best method for extracting samples for moisture determination, this method enables us not only

correctly to determine the site for sampling along a vertical cross-section, but also measure with sufficient accuracy the thickness of individual layers, a point of considerable value in our investigations. Boring may also be used if the structure of the aeration zone is uniform and simple. Such posts should be combined with water inventory plots.

Samples taken from pits (or boreholes) should determine the following hydrophysical properties of the ground in the zone of aeration: specific weight, volumetric weight, porosity, maximum hydroscopicity, maximum molecular moisture capacity, field moisture capacity, capillary lift, coefficient of filtration, and granulometric composition.

The question as to whether repeated samplings are necessary to achieve required accuracy and exclude accidental error, should be decided at the beginning on the basis of a thorough examination of the lithological cross-section.

Given a uniform zone of aeration structure, the moisture reserves along the entire cross-section are calculated from the sampling data, maximum deviations from the mean value being determined by each sample. If the arithmetical mean of this deviation does not exceed 5-8%, the number of chosen sampling repetitions will be sufficient.

A considerably more complex problem of sampling repetitions arises with a variegated lithological structure of the zone and non-uniform surface conditions (fields, forests, plains, slopes, etc.) which influence the degree of its moisture content.

In this instance, repetition of sampling will be dictated not only by the necessity of excluding gross error; it will also be necessary to obtain accurate mean values of moisture content of the extremely variegated lithological species of the ground.

For this purpose the moisture content of different rock in representative areas should be ascertained, particularly along lines of wells or pits located parallel with and across a slope (I. S. Vasiliev, 1950).

The numerical data thus obtained is treated mathematically, the following characteristics being involved in the computation:

n =number of observations;

M=arithmetical mean value of the moisture content in volume;

d=absolute deviation from M for one observation;

$\sigma = \pm\sqrt{\frac{\Sigma d^2}{n-1}}$ standard deviation;

$V = \frac{\sigma \cdot 100}{M}\%$ variation coefficient;

$p = \frac{V}{\sqrt{n}}$ accuracy of the experiment.

The variation coefficient V is the exponent of the moisture content change in any rock bed.

It follows from the formula $P = \frac{V}{\sqrt{n}}$, that if V is not subject to considerable change, the accuracy of the experiment (P) is inversely proportionate to the square root of the number of repetitions (n). Consequently,

$$n_2 = n_1 \left(\frac{P_1}{P_2}\right)^2$$

where n_1, P_1=number of repetitions and the accuracy of our experiment (sampling of earth);

n_2=number of repetitions sought to obtain the accuracy P_2.

Thus, on the basis of our experiment, by taking the values n and P_1, for each investigated layer (or vertical interval), and having predetermined the degree of accuracy desired (P_2), we may arrive at the number of repetitions n_2 required.

According to I. S. Vasiliev (who conducted investigations for determining sampling repetitions of soil and sandy loams), in order to obtain an accuracy $P = \pm 5\%$, the number of required repetitions have been found to be from 4 to 16. Having calculated the arithmetical mean value of volumetric moisture content for each interval of vertical profile and multiplied it by corresponding thicknesses of intervals, one may determine the reserve of moisture in the aeration zone by summing up the reserves of individual intervals.

For an accurate determination of water content in the zone of aeration, samples should be taken every 20-25 cm. along its vertical section and at 10 cm. intervals in its upper belt (1 or 2 m. thick).

Moisture reserves should be computed as frequently as possible (not less than once or twice a month). At water inventory plots in irrigated areas, sampling should coincide with the periods just preceding and following the watering cycle. At each sampling, the water table level must be registered with an accuracy of up to 1 cm.

Following the above study (moisture content in the zone of aeration and level fluctuations of the water table), an estimate may be made of the water balance in the soil-ground prism.

If the water table (at the beginning of observations) and the ground surface are taken as the limits of the prism, then the balance equation may be written in the following manner:

$$p\Delta H + C_2 - C_1 = \left(W_a + \frac{\Delta q}{\Delta x}\right)\Delta t, \qquad (13)$$

where p = porosity of the ground within the zone of fluctuations of the ground water table;

ΔH = variations of the ground water table during the given period of observations Δt;

C_1 = moisture reserves in the zone of aeration (at the beginning of the observation period) from the surface down to the water table;

C_2 = same at the end of the observation period;

W_a = the value of moisture exchange between the zone of aeration and the atmosphere;

$\frac{\Delta q}{\Delta x}$ = difference between underground water inflow and outflow as applied to one unit of the area of the plot.

When calculating the value of $\frac{\Delta q}{\Delta x}$ the actual level of ground waters in three observation borings located along the flow of ground waters within the limits of the water balance site should be used.

Hence, during the given time interval nearly all components of the equation (13) are determined experimentally. The unknown value of moisture exchange between the zone of aeration and the atmosphere (W_a) will be equal to the difference between the left member of the equation (13) and the known term $\frac{\Delta q}{\Delta x}$ of the right member.

A knowledge of the value of W_a is of great practical interest; when this value is negative it represents the total soil evaporation (including transpiration by vegetation), while when positive it indicates the total amount of feed in the zone of aeration through atmospheric moisture and infiltration of irrigation waters.

Such fundamentals of moisture exchange between the zone of aeration and the atmosphere give us the needed data for artificial regulation of the soil-ground moisture content required for plant vegetation. This question directly involves closer watering norms in irrigation.

By comparing variations in moisture reserves for individual belts of the zone of aeration it is possible to find the direction of moisture movement during the given observation period.

Thus, if there has been an addition of moisture from the atmosphere (when W_a is positive), then by comparing this value with the accumulation or loss of moisture in the upper horizons of the zone it is possible to determine the amount of moisture transferred into the lower belts of the zone. When there is a much greater accumulation of moisture in the upper levels of the soil-ground as compared to the amount coming from the atmosphere, it serves as evidence of moisture transfer from deeper lying layers to upper ones, the upper layers receiving additional moisture through two sources of inflow: the atmosphere and deeper lying levels. Such a phenomenon is particularly observed in the autumn when the ground is cooling and the quantity of precipitation increasing.

Moisture exchange between the zone of aeration and phreatic flow is revealed either with the aid of underground lysimeters or on the basis of a mathematical analysis of water table fluctuations, i. e., by the use of unsteady movement equations in finite differences (equations Nos 5,6 and 7).

In addition to the usual meteorological surveys for interpreting the moisture movement in the zone of aeration at experimental balance plots, observations should also include temperatures of the ground and of phreatic waters, aboveground temperature, vapour elasticity in the ground pores and in the aboveground atmospheric layer, etc.

Ground temperatures should be observed within the space beginning from the ground surface to the capillary zone; in doing this, the first Savinov thermometer should be placed level with the ground (the mercury bulb slightly covered with sand) and four others located at depths of 5, 10, 15 and 20 centimetres from the surface.

Ordinary soil thermometers for depth measurements are to be installed at depths of 0.40, 0.80, 1.60 and 3.20 metres (and sometimes at shorter intervals) in accordance with the usual practice of meteorological stations.

Recordings of free ground water temperatures form a part of the general investigations of the balance and regime of free ground waters; thermometric observations in the zone of aeration in the form of thermoisopleths will give a very clear picture of conditions and causes of descending and rising movements of moisture in the zone of aeration; special "lazy" thermometres should be constantly suspended in boreholes at different depths from the water table, including those reaching the water-tight bed of the aquifer.

The temperature and humidity of the overground air layer should also be looked into: ordinary time-lag, maximum and minimum air thermometers should be secured near the Savinov thermometers at heights of 2 or 3 cm. above the ground.

Air humidity should be gauged by psychrometers suspended at various heights (2-3 cm., 40 cm., and approximately 1 and 2 metres above the ground).

The elasticity of water vapours contained in the air of the soil-ground pores should be studied with Lebedev soil hydrographs.

Elasticity observations of water vapours will disclose the causes of variations in the speed of soil evaporation and the conditions of thermal condensation.

Automatic recordings are also of great value; here use is made of self-recorders for level fluctuations, hydrographs to follow daily variations of air humidity, thermographs to keep track of air temperature irregularities, etc.

F) FORECASTING WITH THE AID OF THE FREE GROUND WATER INVENTORY

A forecast of variations in phreatic water levels (a prediction of the waters' regime) on a given territory (variations caused by artificial factors such as irrigation, drainage, etc.) is an inverse problem compared to water inventories as discussed above..

Unknown and variable thicknesses of flow and pressure-heads are ascertained by the equations for unsteady movement in finite differences (5), (6), (7). The values of all other quantities comprising these equations should be known in advance. The amount of recharge (w) must correspond to the future water regime of the territories proposed for irrigation or drainage. Furthermore, this amount will also depend upon meteorological conditions determined by long-term observations.

To secure figures on ground water recharge required for forecasting, analyses of the regime and balance of free ground waters on the given territory should be conducted beforehand, with wide use of the method of analogy, i. e., by employing the principle of investigating ground water regimes in regions with similar conditions of hydrogeology and water supply.

It is therefore very important to study the ground water regime and analyze it hydrodynamically (as given above) on existing irrigated areas where, other conditions being equal (hydrogeological structure, climate, etc.), it is possible to establish a relationship between recharge of ground waters and conditions of irrigation and land drainage.

Forecasting ground water levels in the vicinity of rivers, reservoirs and large canals, all cut perpendicularly by lines of boreholes, is a simpler matter. Since ground water fluctuations in these areas depend principally on changes of horizon in the above bodies of water, a knowledge of such chronological variations of horizon is needed to anticipate the phreatic water table. Constants of infiltration recharge of the underground flow for corresponding annual seasons may be taken from previous analyses of the phreatic water regime.

CHAPTER IV

PROCESSING OF DATA ON THE REGIME OF UNDERGROUND WATERS

1. COLLECTION OF DATA

Observations of the regime of underground waters are to be conducted directly by hydrogeological stations in accordance with the methods already cited.

The schedule of observations will be contingent upon their purpose. Information gathered by observers should be dispatched every month to the station where it is to be specially analyzed.

The following collection schedule should be augmented with material gathered from other institutions.

a. Hydrogeological stations should gather *geological, hydrogeological, soil, topogeodesic and other data.* Everything revealed by bore wells at any time on the territory covered by the station should be concentrated at the latter. Conclusions relating to underground waters must be based upon geological fundamentals. For this reason stations must make use of absolutely all information contributing to more precise determinations of the geological and lithological structures of the given territory.

When collecting geological data the station's hydrogeologist must bear in mind that in individual cases geological factors are dominant and determine the development of separate processes in the regime of underground water.

b. The importance of *meteorology* cannot be minimized. A systematic study of air temperature variations will reveal the relation between such changes in temperatures and those of underground waters, between temperature variations and chemical composition of underground waters, and

will explain fluctuations in the latter's level. All this information should be available at the station for proper analyses of ground water regimes. Therefore, the Meteorological Service should be requested to furnish not only its daily bulletins, but also figures of average annual and monthly temperature.

Precipitation plays a big role in the regime of underground waters. Accordingly, analyses of changes in this regime should take precipitate quantities into account. Underground recharge, however, is influenced not only by the amount, but also by the frequency and intensity of precipitation; this requires that not only the quantity of annual and monthly rainfall in the given areas be known, but also its dates, nature and intensity. Furthermore, individual heavy rains (downpours), heavy snowfalls, violent sills, etc., should also be recorded. Hydrogeological stations engaged in ground water inventory are especially in need of thorough registrations of atmospheric precipitates for the study of all elements of the water balance, particularly those concerning infiltrated water.

Evaporation from the surfaces of the terrain and from open waters, as well as transpiration by vegetation are universal occurrences and their proper recording for the analysis of underground water regimes is extremely important; for evaporation causes variations both in level and chemical composition of ground waters. In this it is aided by intensive insolation, particularly in southern latitudes. In such regions atmospheric precipitates evaporate almost entirely leaving no water for run-off or percolation. Another strong factor in evaporation is the wind.

Although it is difficult to precisely fix all the above evaporation values, the station should be sure to obtain all evaporation data gathered by meteorological posts.

Humidity is very consequential in condensation of atmospheric moisture for the replenishment of underground water. Furthermore, humidity is one of the determining factors in evaporation. Therefore, records should be kept of monthly and daily humidity and saturation deficit, both absolute and average.

Fluctuations in underground water levels, occurring only in wells and other observation workings as a result of changes

in barometric pressure are called by N. N. Bindeman "apparent" fluctuations. They are largely ascribed to variations in the hydrostatic head or to changes in the ratio of this head and atmospheric pressure.

To investigate the effect of atmospheric pressure upon the regime of underground waters, a close study of the relation between atmospheric pressure and the level of underground waters should be made. To properly analyze the actual causes of level fluctuations, daily bulletins of atmospheric pressure must be at the disposal of hydrogeological stations.

c. To establish the link of underground and aboveground waters, hydrogeological stations should collect pertinent *hydrological data*. The interrelation of surface and underground waters will be revealed by observing fluctuations in level, temperature and chemical composition of surface waters and determining their discharge.

Material on hydrology gained from the stations own observations should be augmented with data obtained from corresponding posts of other institutions.

Surveys of river (or lake) fluctuations will also contribute much to the study of underground water regimes, the results of such studies being of great value in the solution of a number of practical and theoretical problems. Furthermore, to carry out analyses of underground waters the hydrogeological station should have at its disposal material on surface run-off from the given territories or basins. This data should embrace not only average monthly and annual fluctuations in level, discharge and temperatures but also chemical composition of these surface waters.

d. Hydrogeological stations should collect all facts relative to the *influence of artificial forces* upon underground water regimes.

On irrigated and reclaimed land hydrometric surveys assume particular importance in the planning and recording of water supplied to irrigated fields. Water flowing along the various channels is computed with the aid of weirs. Stations should collect as much data as possible concerning the above. All water-gauge posts in each given region should be inspected regularly and their location mapped. The map should also show all main and distribu-

tion channels and precise contour lines of the areas attached to each channel.

The results of both daily and average observations must be available at each hydrometric post. This should include information on chemical composition of the water, as well as the quantity and composition of suspended silts entering the irrigation fields together with the water.

All the above material must be interrelated with the underground water regime on the territory being irrigated.

2. METHODS OF PROCESSING DATA ON UNDERGROUND WATER REGIMES

Until recently methods of processing data on regime observations have had principally to do with the study of level fluctuations of underground waters. Instructions in their greater part have refrained from long-term analyses of interrelations between level fluctuations and variations in chemical composition and temperatures.

Facts obtained have ordinarily been given in tabular form. Our treatment is represented by graphic methods, since the regularities of underground water regimes and the interrelation of certain of its phenomena are best revealed in a single combined diagram, with subsequent introduction of variations in level, temperature, chemical composition and other principal factors.

When basic factors are not yet known, those which may effect the underground water regime should be plotted on the diagram, i. e., air temperature variations, quantity of precipitation, changes of surface flow or levels of surface basins, and barometric pressure.

Such a diagram of an annual cycle of observations gives a clear representation of varying factors and is helpful in revealing the basic laws governing the regime of underground waters.

It is possible to clarify a good many interesting facts with the aid of such a chart. We present an example compiled from observations of the underground water regime at a certain post in the course of one year, use also having

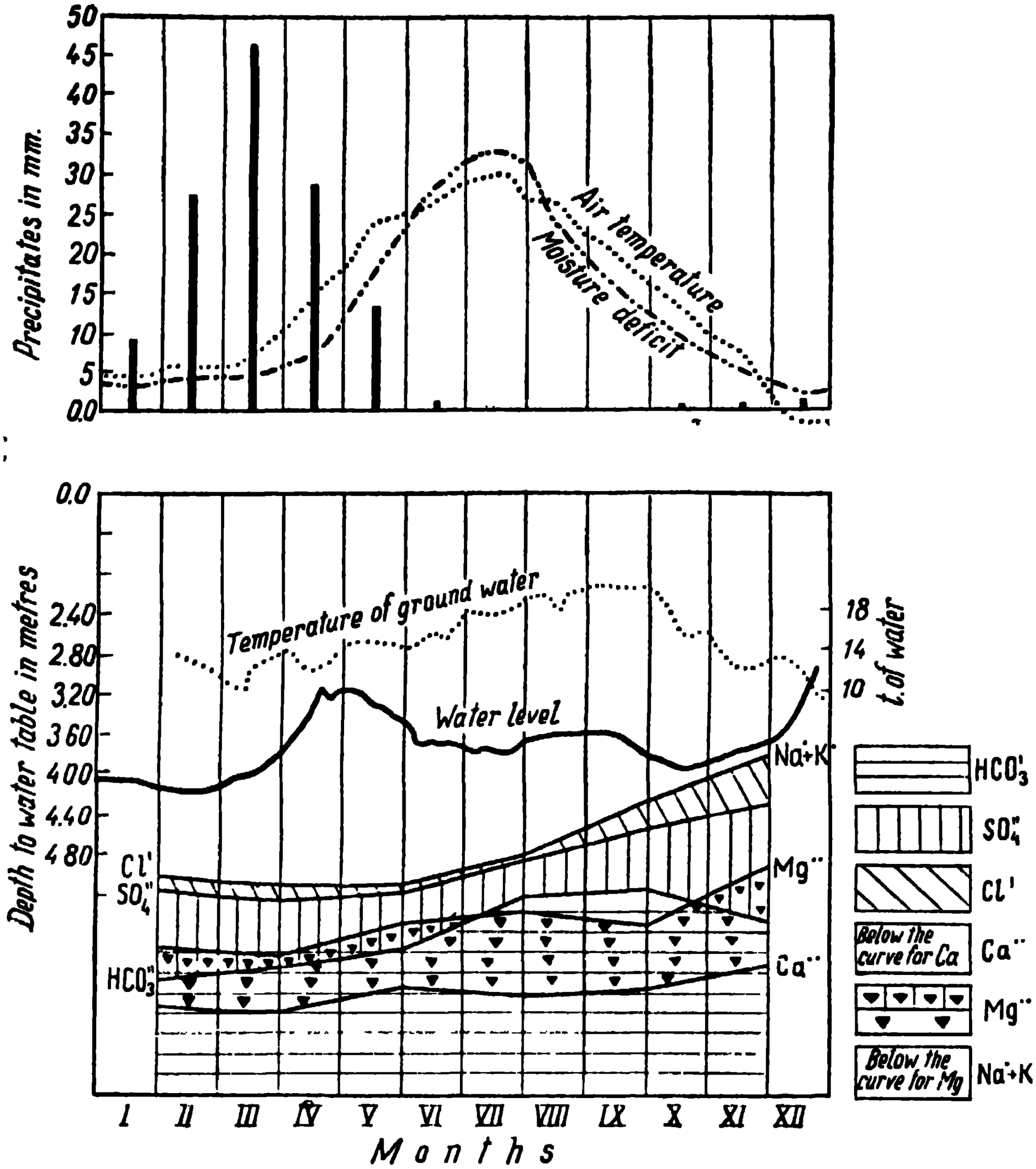

Fig. 47. Fluctuation curves of water level, temperature, and chemical composition of ground waters, depending upon meteorological factors affecting its regime.

been made of information received from a neighbouring meteorological station (Fig. 47).

The diagram establishes a number of interesting natural phenomena with regard to variations in level, temperature and chemical composition of ground waters, subservient to meteorological factors. It shows that water level fluctuations are in direct relation to precipitation and

moisture deficit in the air. As may be seen, the water level in the well began to rise following abundant spring rains. Subsequently, with an increasing moisture and temperature deficit of the air and a cessation of rain, a gradual fall of level commenced. With a decline in temperature and moisture deficit during the autumn months the level began to rise again, although there was a very negligible amount of precipitates.

The chemical composition of the underground water likewise changed: a gradual increase of hydrocarbonate and calcium content occurred in the spring, with a certain decrease in sulphates. Total mineralization remained almost unchanged at this time. In the summer there was a considerable growth in the content of hydrocarbonates and a decrease in sulphates and chlorine, although the ratio of individual cations remained more or less constant. In the autumn, together with a drop in level, the sulphate and chlorine content, as well as the general mineralization of the water, began to rise appreciably.

Variations in chemical composition of the water may be later coordinated with the changes in water-soluble salts in the zone of aeration.

The above primary analyses of information obtained from one observation point is far from complete; the underground water regime was coordinated neither with the local aeration zone and geology and lithology of the rock series, nor with observations from adjacent points, or with records of preceding years, etc. All such omissions must be filled in if a comprehensive and thorough inquiry is to be made into the subject. For only a proper consideration of these factors can establish the underlying principles of the phenomena.

Besides the diagrams mentioned above, the analyses require the combining of individual charts for each element (level, temperature, etc.) into one sheet for different observation points. Such a compilation will greatly help in disclosing the laws governing the regime of underground waters on the entire territory covered by a given hydrogeological station.

When treating the information it is expedient to chart hydrochemical profiles for equal dates.

The most interesting and practical delineation of the

results obtained from the study is the compilation of various maps. These should include maps of hydrogeological divisions showing the types of underground water regimes, chemical maps, and maps with contours of the water table or with isopiestic lines. For irrigated areas, maps showing the depth of acquifer occurrence at different dates should be drawn up.

3. PREPARATION OF ANNUAL AND SUMMARY REPORTS ON THE OPERATION OF HYDROGEOLOGICAL STATIONS

Information derived from observations, as well as that received from other sources, should be presented in the form of reports after proper processing and analysis of all data have been completed.

Observations performed in the course of a current year are drafted in the form of an annual report, while those for each quinquennium are presented as a general (summary) report.

A) THE ANNUAL REPORT

Results of work performed during the year are presented in tabular and graphic form and should be accompanied by an explanatory note, short but sufficiently complete to cover the subject matter.

The annual report should deal with the general activities of the station, its natural environments, and the principal results of its operations during the given period.

A description of the general purpose of the station should be given with an enumeration of themes fulfilled during the year.

Then should follow a brief picture of the natural conditions of the given area, showing its topography, geomorphology, climate, geology, lithology and hydrogeology. If the report of the preceding year contains sufficient details of such generalizations and no appreciable changes had occurred since, a reference to this previous report can be

made with only additional brief notes in regard to the above points. Geological and hydrogeological maps and cross-sections must be appended however.

A review must then be made of results of the work performed by the station, with particular emphasis on:

1. Layout of the observation network and a short description of it, in compliance with its general aims and with the tasks assigned for the year;

2. Equipment and general condition of each observation point, including dates, methods and results of inspection;

3. Methods of observations;

4. Fulfilment of the plan, enumerating and briefly characterizing the work performed;

5. An opinion regarding data received from other organizations concerning the regime of underground water, and the utilization of this material by the station.

Then the report should detail the results of the station's activities, describing and analyzing the underground water regime for each aquifer: variations in level and discharge, temperature and chemical composition of the water in relation to geological and hydrogeological conditions, surface waters, meteorological factors and artificial influences. This analysis should be based on a thorough examination of information covering the entire year under survey; consideration of data obtained during previous years is obligatory.

The report should finish with principal conclusions derived from analyses of the regime of underground waters and methods used in the study, and should include suggestions as to opening of new observation points and closing or reconstructing old posts.

Supplementary material should include:

1. Annual tables of levels, discharges, temperatures and chemical composition of underground waters, as well as meteorological tables.

2. An annual diagram for each observation point, viz., variations of levels, discharges, temperatures and chemical composition of underground waters. Meteorological and hydrological information must also be plotted on each diagram, while for irrigated lands the chart should show actual expenditure of irrigation water.

3. Contour maps of the water table or maps indicating the depth of ground water occurrences.

4. Maps of the chemical composition of underground waters for representative periods of the year (total mineralization, chemical composition according to the dominant ion, etc.).

5. Geological and hydrogeological maps; the latter should include boundaries of hydrogeological divisions and show the locations of observation and hydrometric points and meteorological stations. This map should also show all boreholes and wells, even if they are not a part of the given network.

6. Hydrogeological profiles (cross-sections) bearing descriptions of their permeability and giving filter positions in observation wells.

7. Combined diagrams of individual elements of the regime (levels, discharge, temperatures, chemical composition), including plotted meteorological and hydrogeological data either for each group of observation points in individual hydrogeological divisions or for each profile (cross-sections).

8. Charts of test pumping and other experimental work.

Scales of maps will depend upon the area embraced and the complexity of the map. Diagrams (levels, temperatures, and chemical composition) should be drawn to accepted scales.

B) THE GENERAL (SUMMARY) REPORT

The summary report should be composed of two parts.

The first should describe the region administratively, geologically and climatically, illustrating the degree to which the territory has been explored and presenting a brief review and criticism of available material, both published and in file form, relative to meteorology, hydrology, geology, hydrogeology and especially on regimes of underground water.

A description should be given of the region's climate, orography, hydrography, and geological structure, including the main features of its stratigraphy, lithology, tectonics, geomorphology and physical-geological phenomena (karst, landslides, washouts, subsidence, etc.).

Then should follow an account of hydrogeological conditions, embracing individual aquifers, their areas, depth and conditions of occurrence, lithological composition and thickness of water-bearing rock, permeability and water-yielding capacity, natural outlets, conditions of recharge, movement, drainage and the interrelation in the mineralization of water-bearing horizons.

The review of underground waters should terminate with conclusions apropos the practical importance and utilization possibilities of the aquifers.

Whereas the first half of the report elucidates the general geological and hydrogeological conditions essential to the regime of underground waters, the second part is to describe and appraise the work of the hydrogeological station and the methods applied to the study of the said regime. An account should be given of the observation network and motives for its layout.

Adequate space should be allotted to the regime of the aquifers under study, presenting a detailed description of their investigation and analyses of seasonal and long-range variations in level, discharge, temperature and chemical composition.

Furthermore, a detailed description of the zone of aeration at test sites should be given in which the following sequence is proposed:

a) lithological composition of the rock in the zone of aeration and its physical and chemical properties;

b) a detailed description of investigations;

c) the dynamics of the ground moisture;

d) results of thermometric observations in the zone of aeration;

e) results of observations effected with the aid of experimental installations and devices (lysimeters, evaporators, etc.);

f) evaluation of the role of the zone of aeration in the recharge of ground waters.

It should be noted that a detailed account of the zone of aeration concerns only those stations whose study involves a shallow occurrence of free ground waters.

It is recommended that at this point a qualitative and quantitative analysis should be presented of the relation

of individual elements of the regime between themselves and to natural and artificial factors, and an opinion given on the underground water inventory.

The second part of the report should be concluded by describing the regime of underground water in separate hydrogeological divisions, or in areas with differing natural conditions that cause peculiar features in the regime.

The text of each report will differ according to the type of waters under review—unconfined or confined.

Stations engaged in the study of unconfined waters should describe the hydrogeological laws governing their behaviour as deduced from regime observations, depicting the features peculiar to recharge, movement, drainage, chemical formation, and the relation of water-bearing stratum to surface waters.

For stations whose study involves irrigated regions, a hydrogeological meliorative regional division or a hydrogeological division would be desirable in the presentation of the report (depending upon the general purpose of the station).

Water inventory investigations should be properly represented in the report.

The end of the report should contain an analyzed forecast of ground water regime changes, both under natural and artificial conditions.

An account should be given of the station's aims, and also of the utilization by the national economy of the results of its work.

If the report concerns confined waters, the region should be separated into hydrogeological divisions (following the description of hydrogeological laws), resources of the aquifers computed, and a forecast be given of the regime of confined waters under both natural conditions and during their exploitation.

Then (as in the former case) the report should conclude with an appraisal of the station's compliance with its tasks and the possibility of utilization of the results of its work by the national economy.

Each section of the summary report should be sufficiently illuminated with maps, diagrams, tables and photographs.

4. METHODS OF DIGESTING THE RESULTS OF CHEMICAL ANALYSES OF UNDERGROUND WATERS

The treatment of the results of chemical analyses should reveal:

a) general chemical characteristics of the underground waters in the given region;

b) laws governing the chemical changes in the water of individual horizons, both areal and in time;

c) suitability of the given underground waters, according to their chemical content, for practical use.

This requires consideration of all chemical variations of the water in their relation to geological and hydrogeological environment. For this purpose a comparison should be made of fluctuations in the content of individual mineralization constituents, changes in the ratio of components and of individual groups (for example, anions and cations), changes in the content of constituents with relation to general indices of chemical composition, etc. Since a large number of mineralization components considerably complicate the treatment of the results of chemical analyses, it is best to proceed in several stages, in the order of increasing complexity. There are three such stages:

a) primary systematization on the basis of general laws (this stage is important when there are a great number of analyses, but may be omitted if there are few analyses);

b) a detailed study of variations in the chemical composition of underground waters;

c) map recordings of the laws of variations in the chemical composition of underground waters.

Let us examine each stage separately.

A) PRIMARY SYSTEMATIZATION

Two methods are used (for comparison) in the first stage of systematization of the results of chemical analyses: a) the method of chemical classifications and b) the graphic method. Chemical classifications are often called "genetic"

but in essence no available classification may be so regarded. Such classifications permit the division of chemical analyses into groups according to their chemical characteristics, but these often do not coincide with the basic factors determining the origin of underground waters. Therefore, such classifications cannot be regarded as genetic.

Chemical classifications may be divided into two groups:

a) classifications proposed by Palmer and a number of other authors, the latter actually only representing attempts to add to and correct Palmer;

b) classifications suggested by S. A. Shchukarev and a few others, the latter representing a further development of this classification.

When analyzing the principles of Palmer's classification it becomes evident that it is based solely on variations in the ratio between so-called salinites and alkalinites. This actually indicates the geochemical properties of waters only in the first (alkaline) and fifth (acid) classes. The third class, according to Palmer, includes all other (neutral) waters, these latter embracing the great majority of all types of natural waters.

The idea of salinity and alkalinity forces the union of individual basic components of mineralization into such generalized conceptions as alkaline earths, weak bases, strong acids, weak acids. Alkaline earths include such heterogeneous components of mineralization of underground waters, distinguished by different laws of migration and geochemical history, as calcium, magnesium, chlorine and sulphate-ion. Weak bases combine hydrogen and metals, with the result, in some cases, that waters of the fifth class are actually "acid" according to Palmer, while in other instances, when weak bases are represented by metals alone, they are not acid.

The perception of salinity and alkalinity excludes such important relations as those between chlorine and sulphate-ion and between these two and the hydrocarbonate ion, as well as between calcium and magnesium and these latter and sodium.

Academician B. B. Polynov rightly referred to Palmer's method as an abstract-chemical classification, for in some cases it incorporates genetically different waters into one

class while in other instances waters of the same geochemical nature are labelled in different classes.

No improvement has been attained through the introduction by a number of authors (A. S. Uklonsky in 1925; I. I. Tolstikhin, in 1932, V. A. Sulin, in 1948) of a wider subdivision of this classification. Such a subdivision is not a logical development but rather a mechanical division of the classification and, what is most important, is introduced without criticism of the wrong geochemical supposition of Palmer's classification.

Palmer's classification has been widely used by hydrogeologists, with the result that chemical analyses have very often been limited to a chemical assessment of the water for its practical use. The great possibilities inherent in an analysis of the chemical composition of underground water have not been taken advantage of to demonstrate general hydrogeological processes.

The results of chemical analyses have often been given in milliequivalents per litre and in per cent milliequivalents per litre; all this and Palmer's formula have been offered in the form of a table appended to the end of the report. Thus, this material was not applied to the study of hydrogeological processes.

The classification proposed by S. A. Shchukarev and based on a consideration of the content of six principal mineralization components (Cl, SO_4, HCO_3, Na, Ca, Mg) is much superior to that of Palmer's.

Shchukarev's classification was suggested as far back as 1934. It rests up on six basic constituents with the stipulation that the content of each should exceed 25% milliequivalents per litre. It should be noted that some authors indicate the limits under which individual components should be considered not with a 25% milliequivalent content but with a 10% milliequivalent content.

Each class is subdivided into groups with regard to total mineralization: a) less than 1.5 gram per litre, b) from 1.5 to 10 grams per litre, c) from 10 to 40 grams per litre, and d) more than 40 grams per litre.

In 1935 V. A. Priklonsky, who made Shchukarev's classification more detailed, suggested symbolic indices (with a different placement) for classes of water.

A further development of the classification proposed by S. A. Shchukarev was suggested by O. A. Alekin in 1946, which also suggested the acceptance of six basic components of mineralization for the classification (Fig. 48). First of all, the waters are subdivided into classes according to predominant anion: hydrocarbonate (C), sulphate (S) and

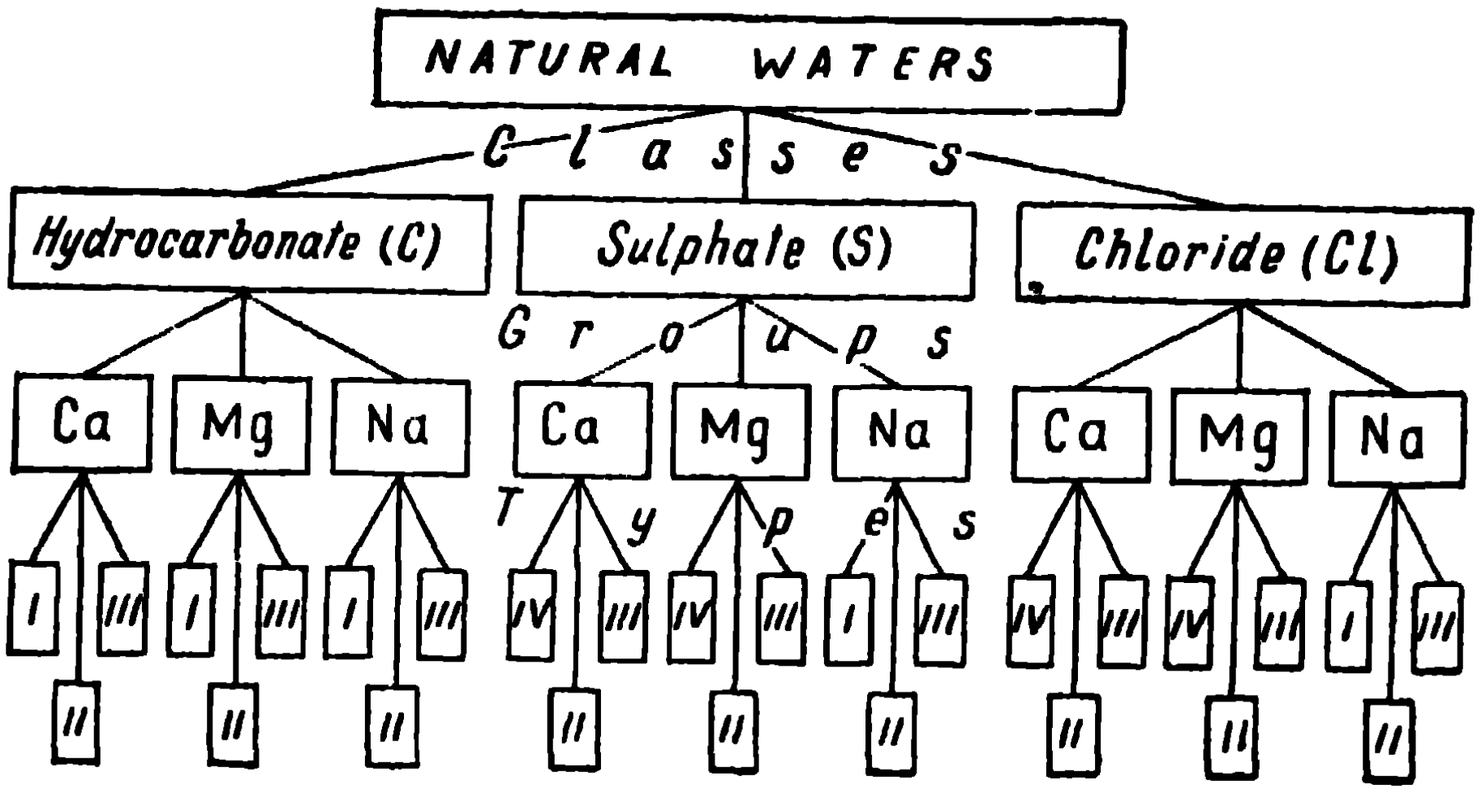

Fig. 48. Classification of natural waters according to O. A. Alekin.

chloride (Cl). According to the prevailing cation each class in its turn falls into groups: calcium, sodium and magnesium. Each group includes the following types:

I. Soft: $HCO_3' > Ca^{\cdot\cdot} + Mg^{\cdot\cdot}$.

II. Hard: $HCO_3' < Ca^{\cdot\cdot} + Mg^{\cdot\cdot}$.

III. Aggressive: $HCO_3' + SO_4'' < Ca^{\cdot\cdot} + Mg^{\cdot\cdot}$.

IV. Acid: $HCO_3' = 0$.

Although the above classifications have many advantages over those of Palmer's, they all have a number of drawbacks in their application for primary systematization.

Primary systematization should be based upon general laws of the widest nature. An example of such laws are the variations in solubility of individual chemical components depending upon the movement of underground waters or the prolongation of their contact with the rock. In a hydrochemical sense this is expressed in the change of ratio between anion and cation components and in the degree of mineralization.

Unfortunately, all classifications (with the exception of those proposed by Shchukarev) fail to consider the degree

of mineralization. This results in the grouping of different waters into one class.

Another disadvantage of all the above classifications (excepting for waters of the "pure" classes where the content in percentage above accepted limits has only one anion and one cation) is the impossibility of distinguishing the dominant anion or cation. On the other hand, in pure classes, where the first dominant anion or cation may be disclosed, the second cannot be determined. But this is of a considerable importance, particularly in primary systematization. For example, chloride-sulphate waters belong to a typical class of zonal waters, while those of chloride-hydrocarbonate content are of the "oil-field" kind.*

It is very important to determine the dominant ion, but at the same time (and particularly for the purpose of primary systematization) the second component in the order of prevalence is also very significant. The classification becomes complicated if these two features are combined. It must be added that "pure" classes are established on the basis of quite arbitrarily chosen limits (for example, 25% milliequivalents per litre, or any other such value, is arbitrarily chosen by various authors).

During the process of mineralization and together with the growth of its magnitude, a considerable variation in dominant anions and cations is observed. A most typical case is given in Table 10.

With increasing mineralization the character of the water changes according to the dominant anions and cations in the following manner:

$[HCO_3 - SO_4; Ca - Mg] \rightarrow [SO_4 - HCO_3; Ca - Na] \rightarrow [SO_4 - Cl; Na - Ca] \rightarrow [Cl - SO_4; Na - Mg]$.

This table gives a very general and approximate idea of the character of variations in mineralization of underground waters, depending upon their movement and contact with the surrounding rock. In considering this relation of water and rock, only very general factors are taken into

*The designation of waters according to chemical composition may be done in two ways. In one method, first place is given to the 1st dominant anion or cation, followed by the second in the order of prevalence. In the other method the sequence of designation is reversed. In this manual the first method is used.

Table 10

Amount of solid residue in grams per litre	< 1	1—5	5—30	>30
First dominant anion	HCO_3	SO_4		Cl
Second dominant anion	SO_4	HCO_3	Cl	SO_4
First dominant cation	Ca		Na	
Second dominant cation	Mg	Na	Ca	Mg

account: for the rock—only the most prevalent water-soluble salts, such as carbonates of calcium and magnesium, calcium sulphates (gypsum) and sodium chlorides; for the water—only the sequence of solubility of these salts under the simplest hydrogeological conditions. This sequence is as follows: the least soluble are carbonates of calcium and magnesium; the more soluble are the calcium sulphates, while sodium chlorides have the highest solubility.

The approximate character of the above table consists in the proximity of the amount of solid residue taken as limits beyond which variations in the dominant anions and cations begin to set in.

The unit value of 1 gram per litre for the solid residue has been chosen because in most instances waters with dominant HCO_3 ion have solid residues not in excess of 1 gram per litre. 5 grams per litre represents the double value of the average solubility of the calcium sulphate.

Sea waters are the most prevalent with the total value of their mineralization reaching 35 grams per litre and comprising $Cl—SO_4$, Na—Mg. The limit of transition for these waters is taken somewhat below that figure, and comprises 30 grams per litre.

The table is not exact because variations in the dominant anion occur with the total value of mineralization differing somewhat from the variations in the dominant cation.

There are very few instances in nature when variations in the composition of mineralization (at its total increase) occur in full conformity with the above-stated scheme. Nature is too manifold to permit any phenomenon to be influenced by only certain chief factors; there are always other causes acting concurrently and complicating the action. Each deviation from the scheme reveals more and more the definite causes underlying the process as a whole.

Chemical analyses of natural waters disclose that changes of ratio of dominant cations and anions, just as the appearance of new combinations of cations and anions (for example, as in magnesium, hydrocarbonate-chloride, chloride-hydrocarbonate waters, etc.) take place in other mineralization values. Each of these variations corresponds to concrete geological and hydrogeological conditions.

By comparing these variations with the stated scheme a primary systematization of chemical analyses of underground waters may be made applicable to given hydrogeological conditions. The principal feature of such a systematization should be the ratio of dominant anions and cations, both with regard to total mineralization of the water and between themselves. A primary systematization requires, firstly, the determination of the dominant components out of the six basic ones. The quantitative indications for the ratio of components should be established by means of definite investigations of variations in the contents of each component, and not by setting up artificial gradations.

One method of expressing the main features of the chemical composition of the water is the use of symbolic indices. A list of such indices of underground waters according to chemical composition is given in table 11.

Table 11

1st dominant anion	HCO_3		SO_4		Cl	
2nd dominant anion	SO_4	Cl	HCO_3	Cl	HCO_3	SO_4
Nos of indices of anion composition	I	II	III	IV	V	VI

1st dominant cation	Ca		Mg		Na	
2nd dominant cation	Mg	Na	Ca	Na	Ca	Mg
Nos of indices of cation composition	1	2	3	4	5	6
Amounts of solid residue in gr. per ltr.	<1	1—5	5—30	>30		
Indices for the amounts of solid residue	A	B	C	D		

In indexing the chemical composition of underground waters in accordance with Table 8, anions and cations are expressed in milliequivalents.

The following water analysis is given as an example in the use of the indices (Table 12):

Table 12

Nos of analysis	Dry residue mg/ltr.	Cl		SO_4		HCO_3		Na+K		Ca		Mg	
		mg/l	mg-eq/l	mg/l	mg-eq/l	mg/l	mg-eq/l	mg/l	mg-eq/l	mg/l	mg-eq/l	mg/l	mg-eq/l
81	340	32.4	0.91	53.5	1.11	169.5	2.68	31.2	1.36	52.1	2.60	8.24	0.68

The index of this analysis will be I_2A.

The use of indices on maps and profiles (cross-sections) permits a concise illustration of the results of chemical analyses of underground waters and the main features of the relation between chemical composition and hydrogeological forces.

In the text the indices should be written in the form of pseudo-fractions, numerators showing anions in their decreasing order, and denominators indicating the cations. Third anions and cations are not shown at all in these fractions. A symbolic designation of the mineralization

value is written on the right of the fraction. For example, the index I_2A assumes the following fractional form: $\frac{HCO_3—SO_4}{Ca—Na}A$. Instead of an index, any particular water may be named in the text. In the above example (Table 12) the water could be designated as hydrocarbonate-sulphate, calcium-sodium.

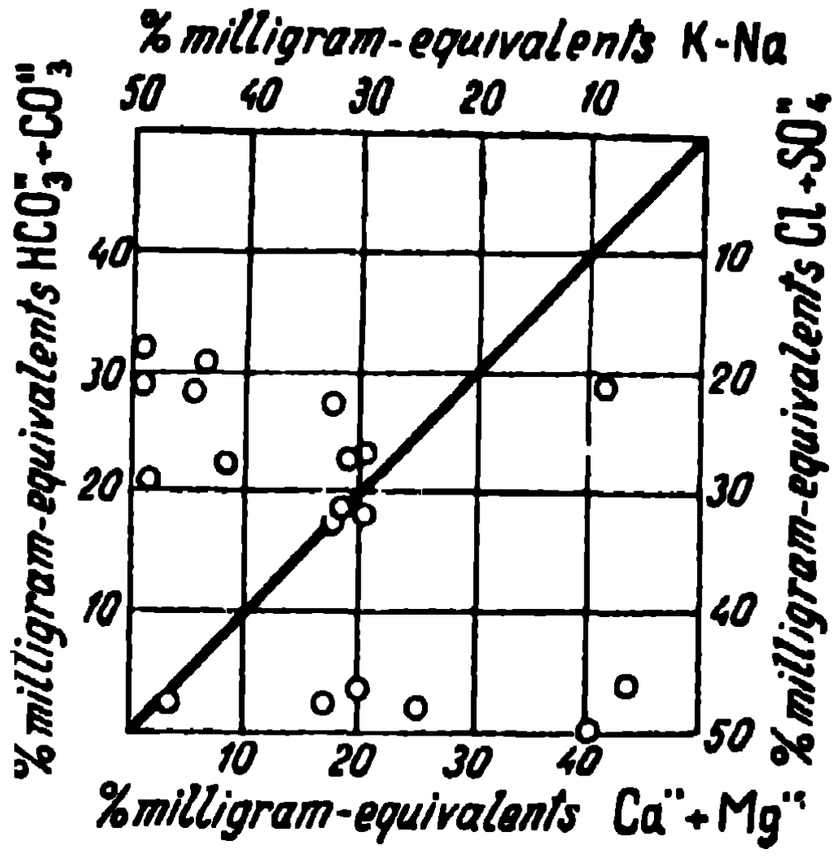

Fig. 49. Square graph proposed by N. I. Tolstikhin.

The aforementioned gradation of the value for total mineralization should be used for large regions embracing different zones of water mineralization. For small regions of only one zone of mineralization, other types of gradations may be used. Thus, one may take the following gradations if a mineralization value does not exceed 3 grams per litre: a) up to 200 mg/ltr, b) from 200 to 500 mg/ltr, c) from 500 to 1,000 mg/ltr, d) from 1,000 to 2,000 mg/ltr, and e) exceeding 2,000 mg/ltr. To indicate that the gradations are arbitrary they should be written in small letters. In the text the multiplier of the pseudo-fraction repre-

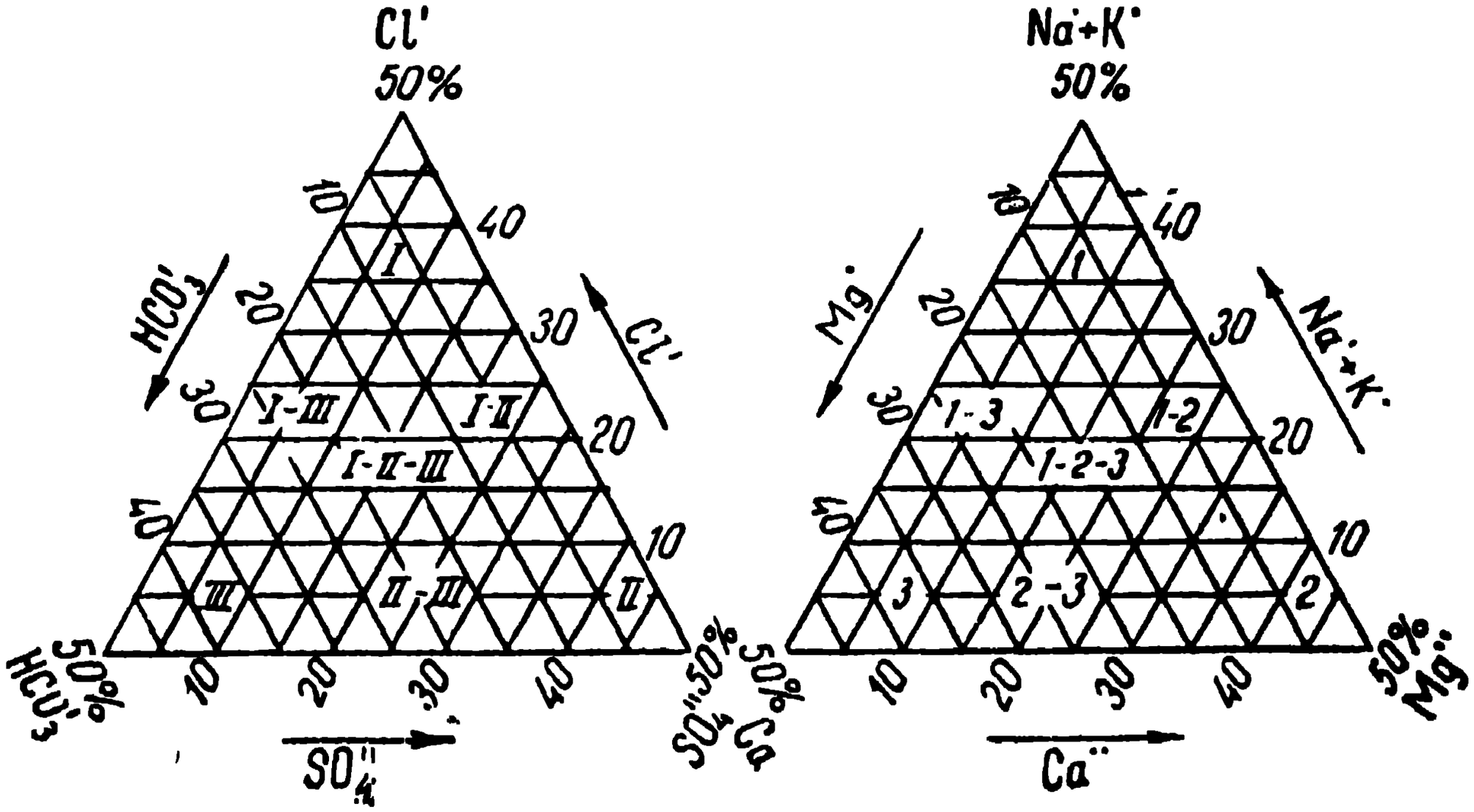

Fig. 50. Representation of Shchukarev's classification in a triangular graph.

senting the value of mineralization may be designated by a figure showing the mineralization value in grams per litre; for example, the above cited chemical analysis would be shown in the following manner:

$$\frac{HCO_3SO_4}{Ca\ Na}0.34.$$

For a more detailed illustration of a chemical analysis of underground waters a formula proposed by Kurlov may be used, which concisely describes a given chemical analysis. However, its application in primary systematization and plotting on a map or profile is difficult because of its relative bulkiness.

Two types of diagrams are used for the graphic systematization of the results of chemical analyses: a square line graph as proposed by N. I. Tolstikhin (Fig. 49) and that in the form of a triangle (Fig. 50).

The distribution of points for each analysis on the square line graph depends upon the quantity of weak and strong acids, upon alkalies, and upon the sum of alkali-earth elements; this is the weak part of the diagram, for it is impossible to group the analyses according to basic features of a chemical composition suitable to separate ratios of Ca and Mg content and the content of Cl and SO_4.

The diagram in the form of a triangle compiled individually for anions and cations is free of this defect, but the disjointed representation of anions and cations confuses the comparison of changes in the cation and anion composition. And this, as has already been pointed out, is one of the most important features in primary systematization. Depicting the variations in anion and cation composition by means of different legends on one triangular graph does not facilitate the work.

The most convenient graphic method in primary systematization consists in plotting analyses of chemical composition of underground waters on a square chart as shown in Fig. 51: here mineralization values are denoted by conventional signs (see figure). Let us say that the analysis plotted on the diagram has a dry residue amounting to 1 gram per litre. Then the method of plotting is similar to the one for the compilation of indices described before.

After the analysis has been plotted it is possible to determine precisely the chemical type of underground waters prevailing in the given region. The diagram clearly illustrates variations in the character of mineralization contingent upon changes of its values, and accurately distinguishes other types of waters. The use of this diagram has been described in detail in the work of A. A. Brodsky, published in 1953.

The grouping of analyses shown on the above square chart should be well coordinated with geological and hydrogeological conditions by showing the signs in different colours or shades. In this way it will be possible to distinguish, for example, regions of underground recharge, deep circulation and discharge, waters occurring in alluvial deposits and weathering joints of effusive rock, flows belonging to different hydrogeological regions, etc.

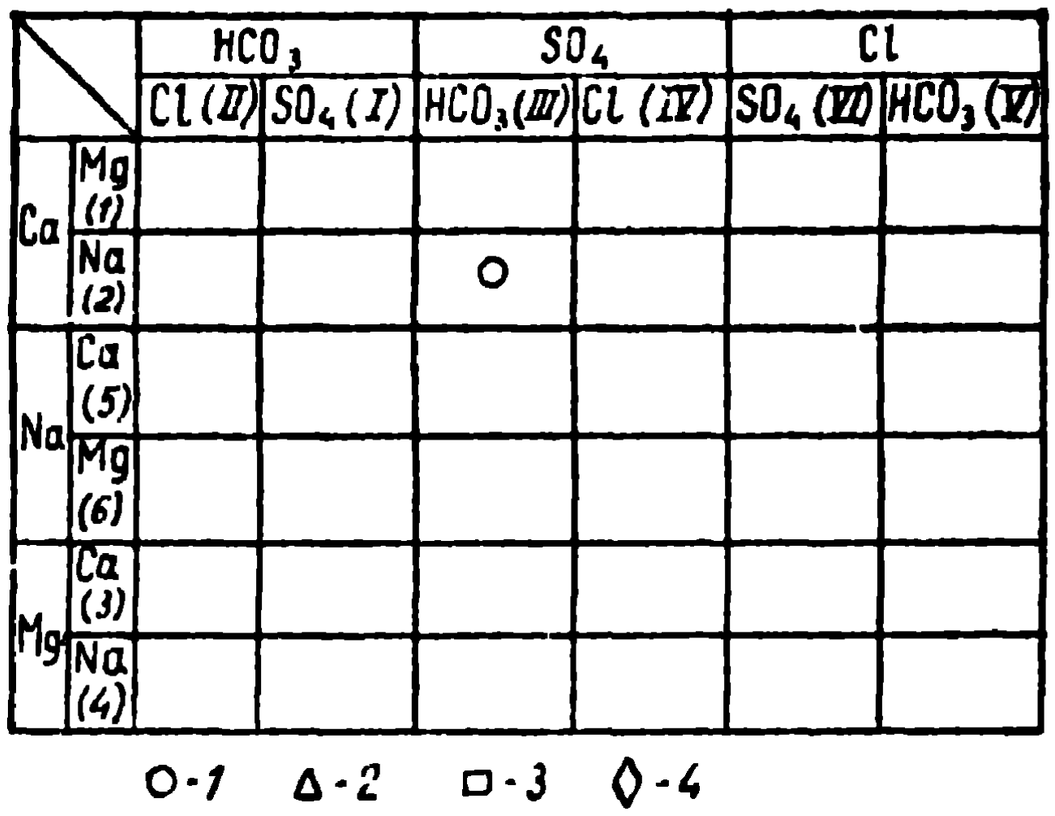

Fig. 51. Square chart for representin chemical composition of ground water. Dry residue: *1*—up to one gram per litre; *2*—from 1 to 5 gr/ltr.; *3*—from 5 to 30 gr/ltr.; *4*—over 30gr/ltr.

A great aid in such coordination is the plotting of indices on a hydrogeological map. A number of cases may be encountered: either most of the analyses on one square will conform to approximately equal hydrogeological conditions, or, depending upon existing conditions they will fall into several groups. Such a grouping on the chart arranged in accordance to hydrogeological conditions will represent a primary systematization and afford an idea as to the general laws of positional changes in the chemical composition of underground waters and the process of their development.

The distribution of analyses on this diagram will reveal the hydrochemical zone to which underground waters of the given region belong, peculiarities of this zone, and the

intensity and manner in which the influence of various processes pertaining to mineralization formation make themselves apparent.

Besides large analyses groups, each square may contain a single analysis differing from the general run either by its degree of total mineralization or by hydrogeological environment. Individual squares may, in general, contain only separate analyses. All the geological and hydrogeological conditions contributing to the formation of the chemical composition of underground waters represented by these single analyses should be carefully studied.

It is thus seen that a primary systematization executed with the aid of the square chart will differentiate typical groups of analyses, reveal basic features of development and types of chemical composition of the given region, and suggest the most general interrelation between the chemical composition of the underground waters and their geological and hydrogeological environments.

B) THE DETAILED STUDY OF VARIATIONS IN THE CHEMICAL COMPOSITION OF UNDERGROUND WATERS

The chief feature of a detailed study of variations in the chemical composition of underground waters should be a careful explication of the geological and hydrogeological forces responsible for such changes, both positionally and chronologically.

This phase of the work, which is very important in investigating the water's regime, is clarified by comparing such changes as they are plotted on geological and hydrogeological prophiles and maps. In addition, diagrams should be drawn illustrating chemical variations in time (see below).

Three principal problems arise when comparing these diagrams with variable factors affecting the chemical composition of underground waters:

1. What factors of geological, hydrogeological and general natural environment should be used for comparison;
2. Which of the mineralization constituents should be compared;

3. What is the best graphic form for the comparisons.

In regard to the first question it should be noted that in studying chemical variations of free ground waters it is necessary that the geological and hydrogeological profiles or maps used for comparison reflect topographic features and lithologic changes in the aquifer and show the impervious bed, the rock of the aeration zone, and variations in the depth of the ground water table. Special conventional signs should be used on the profiles to mark depressions of relief, both with and without water flow. But this is far from sufficient for all cases; for very often it will be necessary to show variations in the kinds and types of vegetation, genetic type and age of sediments, distance from intake or discharge areas, etc.

Often it is impossible to show all these features on one diagram or one map and it may therefore be necessary during the processing of information to make comparisons of a number of maps and profiles.

The graphic material accompanying the report should reflect the most important factors determining variations in the mineralization of ground waters. Prior to detailed comparisons a preliminary examination should be made of the relations existing between the process of mineralization and the general geological and hydrogeological environment. And only then should corresponding profiles and maps be prepared.

The choice of site and direction for such hydrochemical and geologo-hydrogeological profiles is essentially important. In general the profiles should follow the direction of basic variations in the chemical composition of underground waters and their development, beginning from the intake area towards that of discharge. But in many cases it will be important that profiles run perpendicularly to this direction.

A chronological investigation of chemical changes in underground waters demands a comparison of corresponding variations in level or pressure-head, discharge and temperatures and, very often, changes in various meteorological factors, consumption of irrigation waters, etc.

When considering the second item (choice of mineralization components to be taken for comparison) it should be

borne in mind that in most instances variations in six of the basic components, as well as in the total mineralization and PH values, should be used. It will sometimes be found necessary (depending upon chemical composition of the underground water and the purpose of the work) to make use of variations in the content of silicic acid, iron and all the microcomponents.

In individual cases and for simple geological structure and conditions, when the area under investigation is located in a single zone of mineralization, it may be possible to take only one or two mineralization components whose variations are most typical for the given conditions.

There are in the main two methods of illustrating variations in chemical composition of underground waters on the profiles.

1. In the first method, chemical composition is shown in the form of columns whose points of abscissa correspond to the place or time of water sampling.

The columns themselves may be shown in several ways. The method proposed by Rogers repeats all the defects of Palmer's classification and is absolutely unsuitable.

The method of dividing the column into two parts is much better; one half of the column represents anions and the other cations, drawn to a certain scale in % milliequivalents.

The order of representation differs. The following is usually proposed (reading from the bottom up): for anions—$HCO_3 \rightarrow SO_4 \rightarrow Cl$; for cations—$Ca \rightarrow Mg \rightarrow Na + K$. O. A. Alekin introduces a different order (reading from the top down): for anions—$SO_4 \rightarrow HCO_3 \rightarrow Cl$; and for cations—$Ca \rightarrow Mg \rightarrow Na + K$.

But such graphs fail to show variations in absolute quantities of mineralization components. Furthermore, it is hard to read these diagrams along the profile due to the variations of anions and cations.

Because of the same difficulty we cannot consider as adequate the diagram composed of a row of columns each of which represents, at a definite scale, the mineralization content (dry residue) and one of the six basic components of mineralization.

2. The second type of graph consists of curves for each component and for the total mineralization value, the site

or date of sampling being shown along the axis of the abscissae, while the content of the mineralization component is read along the axis of the ordinates. The curve for each component has its own legend.

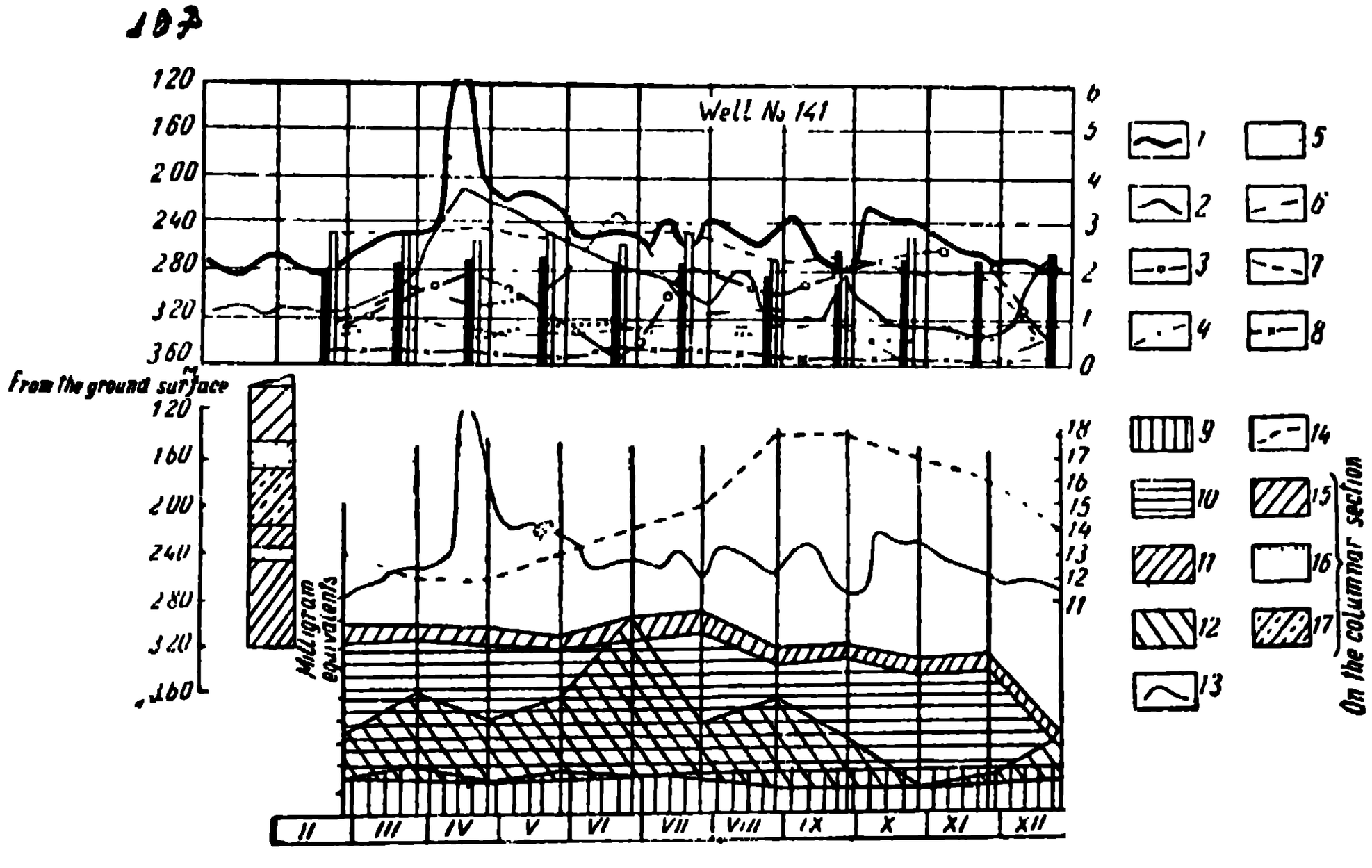

Fig. 52. Diagram showing variations in the chemical composition of ground water.

Upper diagram: *1*—level of ground water; *2*—water temperature; *3*—content of Na^{+} ion in mg ltr.; *4*—content of Mg^{++} ion in mg ltr.; *5*—content of Ca^{++} ion in mg/ltr.; *6*—content of Cl' ion in mg ltr.; *7*—content of SO_4'' ion in mg/ltr.; *8*—content of HCO_3' ion in mg ltr.; Lower diagram: *9*—content of HCO_3'. ion in mg eq/ltr.; *10*—content of SO_4'' ion in mg eq/ltr.; *11*—content of Cl' in mg eq/ltr.; *12*—content of Mg^{++} ion in mg eq/ltr.; *13*—level of ground water; *14*—temperature of water; *15*—clay; *16*—sand; *17*—sandy loam.

With this method it is easy to trace variations in the content of each component along the profile. But the large number of curves (a minimum of seven for the dry residue and the Na+K, Ca, Mg, Cl, SO_4, HCO_3) and the considerable change in content of individual components also make the use of this diagram difficult (Fig. 52, upper diagram).

Besides the two above methods, another way is to plot circles (on the profile) whose diameters are proportional to the total mineralization value. Each circle is divided into sectors; each sector is equal to definite anions or ca-

tions and has its own colour in accordance with the legend. The size of each sector is in direct proportion to the % milliequivalent of a certain cation or anion (1% milliequivalent =3.6°, and the sum of anions and cations is equal to 100%). But even this method presents difficulties in examining the chemical composition along the profile.

The following method is recommended for comparisons: distances at a predetermined scale and representing the sites or time of sampling, and corresponding to the hydrogeological profile, are plotted on a Cartesian coordinate diagram along the axis of the abscissae (see Fig. 52, lower diagram).

The content of the HCO_3 ion expressed in milliequivalents per litre is plotted (also to a predetermined scale) on a perpendicular raised at each point from the axis of the abscissae. Further up, from the points showing the content of the HCO_3 ion, the content of the SO_4 ion is marked off; then from the points indicating the content of the SO_4 ion the content of the Cl ion is also designated. All the points showing the content of the HCO_3 ion as well as the SO_4 and Cl points are then connected by a curve. The space between the axis of the abscissae and the curve uniting the HCO_3 points, as well as that between the curves HCO_3 and SO_4, SO_4 and Cl are cross-hatched or coloured according to the legend.

Then, to the same scale, on the ordinates giving the sites or dates of sampling and from the axis of the abscissae, the Ca content is marked off in milliequivalents; the other markings are: the content of Mg from the point Ca, and from the point Mg—the content of Na+K, all determined either by their differences or analytically and then summarized. All the Ca and Mg points are then united with each other. If Na and K have been correctly determined according to their difference and if the analysis has been computed correctly, the curve uniting the points Na+K should coincide with the curve Cl (the sum of the milliequivalents of anions will be equal to the sum of the milliequivalents of cations).

The area between the curves Ca and Mg is conventionally hatched according to the legend for Mg: if the symbol representing anions is coloured, then the space between

the curves Ca and Mg should be cross-hatched; if the symbol for anions is cross-hatched, the area limited by the curves Ca and Mg is also hatched but in a different manner than for the anions. There is no need to cross-hatch the Ca and Na areas since from the layout of the chemical profile it is clear that the area Na lies above, and the area Ca below. the area Mg.

If the ion system includes a large number of components then silicic acid (ionic) should be placed within the HCO_3 and SO_4 spaces, and the nitric acid above the Cl.

But if there are Pb, Cu, Al, $Fe^{\cdots}$, $Fe^{\cdot\cdot}$, Zn ions among the ions, the areas showing variations in these components will be found between those of the Ca and Mg curves (from the area of the curve Ca) in the order enumerated above. If the system of ions consists of more than six components, conventional colouring and cross-hatching are used, colouring being employed in the system (either anions or cations) which includes the greater number of components and whose readings are of greater importance for the investigation.

On the same chemical profile but somewhat above the Cl curve, another is constructed showing variations in the PH value.

From the diagram thus constructed, variations in the content of each individual component and changes in the ratio between anions and cations can be learned.

The curve Cl shows variations of one half of the sum of milliequivalents and furnishes an idea of changes in mineralization value of the underground waters.

It follows that this diagram clearly illustrates all the principal features accompanying chemical variations typical for the development of underground waters.

This same diagram shows the appearance of alkaline water when the Mg curve descends below the HCO_3 curve, of gypsum (or rather of the equalizing of Ca ions by SO_4 ions) when the Ca curve rises above the HCO_3 curve, and of Mg and Ca chlorides.when the SO_4 curve drops below the Ca curve.

The same diagram also illustrates the change of such an important ratio as $\frac{rNa^{\cdot}}{rCl'}$.

If the Na area is greater than that of Cl, it indicates the possibility of a cation exchange between the rock and water with the transition of Na to the water, or it points to processes associated with the inflow of soda water. If there is a cation exchange, then together with the predominance of Na over Cl there is a decrease in Ca. The predominance of Cl over Na may point to the existence of a cation exchange, but with a transition of Ca to the water. This supposition may be verified by an investigation into changes in the Ca content.

The disclosure of all these processes requires not only the study of the hydrochemical profile, but a comparison with geological and hydrogeological environment.

Although the hydrochemical profile reveals a number of processes, it cannot show, or vaguely reflects, some of the variations in chemical composition. Thus to reveal the formation processes of mineralization it is of the utmost importance in many cases to know the changes in the ratio of $\frac{rCa^{\cdot\cdot}}{rMg^{\cdot\cdot}}$. These changes can be clearly seen on the chemical profile only when there is a considerable difference in the content of Ca and Mg. But it is impossible to perceive these changes on the diagram if the difference is small. In the latter case it becomes necessary to compute the values of $\frac{rCa^{\cdot\cdot}}{rMg^{\cdot\cdot}}$ and then draw a curve somewhat above the chemical profile. This is also true with regard to the ratio $\frac{rCa^{\cdot}}{rCl'}$.

Hydrochemical and hydrogeological profiles should be plotted on a single sheet, one above the other. The scales of the abscissae on both diagrams will be the same and zero will be found on one ordinate. To facilitate the comparison, ordinates common for both diagrams should run through the points showing sampling sites.

In studying chronological chemical fluctuations, the curves showing time changes in level, discharge and temperature of underground waters, and if necessary, various meteorological factors should be traced a little above the chemical composition diagram.

It should not be forgotten that a change of mineralization may be influenced by a transition of underground waters into various lithological complexes, a condition which

is sometimes observed during level fluctuations, either annually or over a period of many years. In such a case a cross-section of the borehole should be drawn (in the same vertical scale) to the left of the curve (see Fig. 52).

Such a diagram may also be used to clarify variations in the mineralization of waters depending upon the depth of their occurrence. For this purpose the points of water sampling (their depths) are marked off on the ordinate with zero situated above to show the ground surface; on the abscissa the component content is indicated.

The same method may also be employed to illustrate variations in water mineralization during test pumping from a borehole: the time lapse from the commencement of pumping is marked off on the abscissa while the ordinate is made to show the content of mineralization components in the same way as described above.

Curves corresponding to the time indicated on the abscissa and showing water level and discharge are drawn on the same diagram.

A diagram illustrating variations in chemical composition of underground waters during pumping and compiled on the basis of samples may be constructed either above the curves of the previous chart or on a separate sheet.

Another item of considerable consequence is the investigation of chemical composition of underground waters relevant to their changes in total mineralization value; this is done with the aid of the same diagram but with the mineralization value plotted on the axis of the abscissae.

If the number of analyses is large the diagram becomes cumbersome and it should be drawn separately for analyses contained in each individual square of the chart as, for instance, for I_1, III_2, etc.

Comparable hydrochemical profiles should be prepared for those time intervals marked by the most intensive chemical variations. For this, one sheet will carry several profiles corresponding to different dates.

Comparison of hydrochemical and geologo-hydrogeological profiles should be made only along the most important orientations and with obligatory comparisons of data contained in geological and hydrogeological maps.

The simplest way of comparison, involving the plotting of indices on a hydrogeological map, has already been described (see primary systematization). Such a comparison may be executed by drawing circles (divided into coloured sectors) near each sampling point. The diameter of these circles should be proportional to the total mineralization value, while the size of sectors should be equal to % milli-equivalent per litre for each given component.

A more detailed comparison may be made on a geological or hydrogeological map by the plotting of isolines showing the content of a given constituent of mineralization. Such maps are best for showing each constituent separately, only those components being taken whose variations over the given area are not only the most intensive and capricious, but also representative in revealing the relation between changes in chemical composition of the waters and the general geological and hydrogeological environment. Prior to plotting the isolines, the distribution of chemical types of underground waters should be marked by cross-hatching or some other conventional method.

The most complex comparisons on these maps will be those of chronological variations in chemical composition. In individual cases this is done by isolines showing the content of a given constituent in different periods of time.

When the necessity arises to compare a large number of time intervals, isolines corresponding to each such interval are plotted on separate sheets of tracing paper which are then alternately superimposed over the basic map.

There is no need to prepare an excessively large number of diagrams and maps. It should be always borne in mind that they serve an ancillary purpose in disclosing interrelated laws in the chemical composition of underground waters and geologo-hydrogeological conditions.

C) PREPARATION OF SYNTHETIC MAPS

The chief synthetic map of positional variations in chemical composition is the map showing the distribution of chemical types of underground waters.

Maps of chemical types should be compiled, as far as possible, on the basis of simultaneously gathered data. The

collection of this material should be timed to coincide with maximum or minimum mineralization in the greatest number of sampling points. This will greatly facilitate the combining of maps showing types of underground waters with those showing rates of change in chemical composition; for the amount and character of mineralization indicated on the chemical-type chart will ordinarily coincide with the upper or lower limits indicated on the map of chemical changes. The rate of sampling should be indicated on each map. The boundaries between areas with different underground waters should be delineated not only through points bearing corresponding chemical logs; demarcation should also be based on boundaries between regions and zones possessing similar geologo-hydrogeological conditions.

The most representative graphic information should be used as a basis for illustration.

The map should include:

1) areas where the quantitative variations in underground water mineralization do not step beyond the bounds set by chemical analysis for the period compiled on the map;

2) areas with variable mineralization but with constant types in conformity with the above stated chemical indices;

3) areas where the amount of mineralization and the type of water are subject to time variation;

4) areas where the mineralization value is constant in time but different in character.

Areas of the second category should be divided into sections, each with its own mineralization variations. For example, areas may be distinguished that show mineralization variations up to 0.5 grams per litre, from 0.5 to 1.0 gr/ltr., from 1 to 3 gr/ltr., etc.

Areas of the third and fourth categories should be subdivided into sections depending upon variations in the character of mineralization; the order of the subdivision should begin with the lower values and go towards the higher. Thus, the order of the sections may be given according to water variations of from $\frac{HCO_3—SO_4}{Ca—Mg}$ 0.5 to $\frac{SO_4—Cl}{Na—Ca}$ 7.0.

In areas of the fourth category where the mineralization value remains almost unchanged, characteristics should begin with the type usually representing the lower degree of mineralization and go towards the higher. For example, the sections may be characterized by the transition of

$$\frac{HCO_3—SO_4}{Ca—Mg}\ 0.8 \text{ to } \frac{SO_4—HCO_3}{Ca—Na}\ 0.8.$$

Not only should chemical analyses be used for demarcating the areas, but the boundaries determined by geological and hydrogeological conditions should also be considered.

A combined map showing time variations and types of chemical composition of underground waters is required for final conclusions. Such a combination usually presents no difficulties, since each type of underground water possesses its own variations in chemical composition. The only complication that may arise is the existence of an area with transition types of water, or one with sharply varying hydrogeological conditions where underground waters are fed by a river during one season of the year, and drained by the river during another.

The combined map may also be a map of chemical types of underground waters, differing from those described before in that it covers a more or less long period (a year or several years); this should be indicated in the subtitle. Such a map will represent a definite concluding stage of investigations of the chemical properties of waters occurring in a given stratum or in a given area. Hydrogeological stations should prepare such maps, both for the annual report (based upon observations covering one year) and for the general (summary) report (taken from data obtained from long-term observations).

The combined map should be accompanied by chemical profiles and diagrams representing depth and time variations in the chemical composition of underground waters for each area affected by such variations.

If the magnitude of variations in the year under survey has been insignificant, a map of the preceding year with a superimposed tracing of such changes can be appended to the report. If there should be considerable variations, it is advis-

able to present a new map and a description of all variations and changes in the text of the report.

Maps illustrating chemical types of underground waters should serve as a basis in practical work. Thus, when solving problems of water supply, these maps help to choose typical analyses (both chronologically and according to areas).

In estimating the reclamation value of any land, these maps aid in distinguishing areas with salt accumulations. They determine whether these accumulations are permanent or incidental to certain years or seasons, define the areas characterized by the wash-off of salts, etc.

Chemical-type maps together with their diagrams and text permit forecasting chemical changes in underground waters caused by artificial factors (various hydrostructures and other undertakings). Such maps are also employed in inaugurating measures relative to changing chemical composition of underground waters for the needs of the national economy.

5. THE PERIODOGRAM AS A METHOD FOR PROCESSING LONG-TERM OBSERVATIONS OF THE LEVEL OF UNDERGROUND WATERS

Revealing periodicity in level fluctuations of ground waters is of paramount importance for the national economy. Periodic fluctuations thus disclosed form a foundation for long-term forecasts used in planned offensives against soil salinization and for compiling schedules of dates and rates of irrigation.

At present the solution of these problems is hindered by the absence of sufficient information on long-term variations in the level of ground waters and methods of treating such data.

The first-mentioned situation may be dealt with only by the organization of systematic, long-period observations of underground water regimes. The latter of the two questions may be solved by one of the methods of processing the results of observations, i.e., the method of periodogram analysis used in mathematical statistics. This involves a number of rather complex and time-consuming mathematical

operations. But there is one very simple form which might find wide use in the practical work of our hydrogeological stations.

The substance of periodogram analysis may be reduced to one very simple idea which may be illustrated by a concrete example. Let us assume that we have data at our disposal concerning variations in the level of ground waters for a two-year period such as listed in Table 13 (relative average monthly levels of ground waters).

Table 13

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1st year	7	6	4	6	20	15	13	11	10	9	8	7
2nd year	6	5	3	5	19	14	12	10	9	8	7	7
Total	13	11	7	11	39	29	25	21	19	17	15	14

In the given case, fluctuations in level of ground waters hold to an annual periodicity. But we will presume this is not known and shall make two assumptions. One, known in advance to be correct, accepts the idea of annual periodicity, while the other, known in advance to be incorrect, assumes a three-month periodicity of the phenomena. Accordingly, to examine the assumption of a 12-month periodicity, we place average monthly levels in 12 consecutive columns beginning with January and add up the figures of each column separately. The results are shown in the third line of Table 13.

To investigate the assumption of a three-month periodicity we will arrange the same data in three consecutive columns, beginning with the first figure of January. Then under the January figure will come that for April, while under the February figure—that for May, etc. As in the first case all figures in each of the three columns are summed up (see Table 14).

Table 14

Average monthly levels			
	7	6	4
	6	20	15
	13	11	10
	9	8	7
	6	5	3
	5	19	14
	12	10	9
	8	7	7
Total:	66	86	69

When comparing the layout of figures in Tables 13 and 14, it becomes evident that due to the correct assumption of periodicity (Table 13), the data was distributed in such a manner that all maximum levels are concentrated in one column and all the minimum ones in the other. But under the wrong assumption (a three-month periodicity) the figures in the columns are distributed at random: maximum levels are in the same columns with minimum ones. As a result, the difference between the maximum sums of Table 13 shows the highest value when the assumption is correct (39—7=32) and the lowest when the supposition is wrong (86—66=20, Table 14). This represents the basic idea of periodogram analysis.

Periodicity may also be revealed directly from a diagram indicating fluctuations in the level of ground waters. But owing to various reasons, the positions of maximum and minimum values on the diagrams usually become shifted to one side or another and this makes the reading somewhat vague. Periodogram analyses are much clearer. Furthermore, the value of this analysis is that it is possible to reveal hidden periodicities that are completely obscured in a diagram.

Let us take a concrete example of the whole course of a periodogram analysis. For this purpose we shall take the data obtained from long-term observations of the level of ground waters in the Kamennaya Steppe.

It should be noted that periodogram analyses may be executed on the basis of varying levels, such as: yearly av-

erages; a maximum average for May months; a minimum average for the months of September; and finally the level for a typical date (let us say, the first of September). However, for a correct treatment it is advisable to simultaneously take a yearly average, maximum monthly averages (let us say, for May months), and minimum monthly averages (September months, for example). We should mention at this point

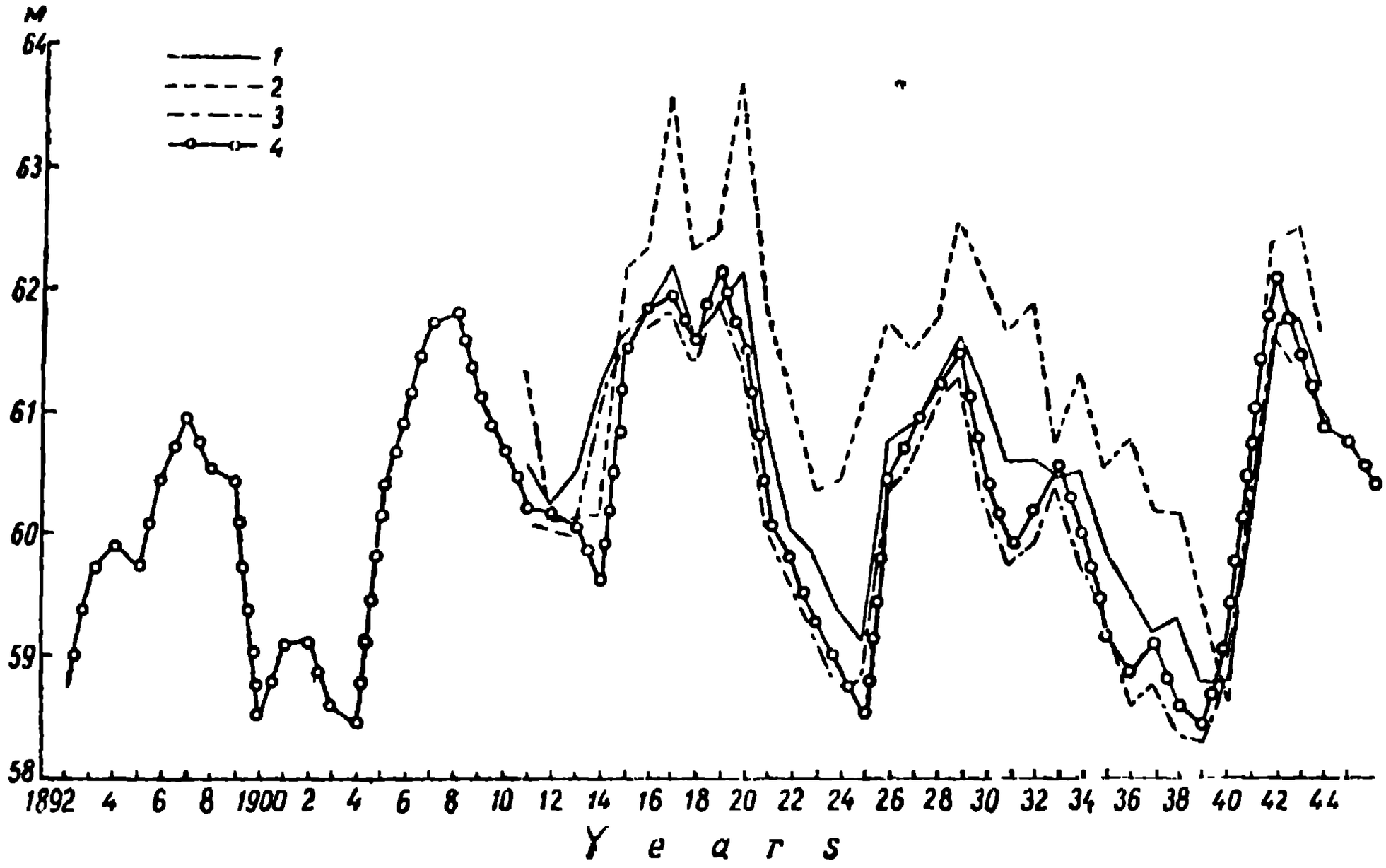

Fig. 53. Fluctuation curves of ground water levels (Kamennaya Steppe, well No. 1).

1—average annual levels; *2*—average levels for the months of May; *3*—average levels for the months of September; *4*—levels of 1/X of each year.

that some investigators underestimate the importance of monthly and yearly averages and maximum and minimum level values. But these figures are necessary in the extreme for analyses of underground water regimes.

Fig. 53 represents fluctuation curves of the water levels in the Kamennaya Steppe (according to an optional benchmark based on a yearly average, averages for May months, averages for September months, and for September lst of each year). An examination of these curves will demonstrate that the general course of variations for many years is a

more or less uniform reflection of both average annual levels and those for any two selected months, as well as those taken for September lst. It may be deduced from the given case that there is a periodicity of 10-14 years. Incidentally, no other periodicity can be seen from this diagram. And yet we have grounds to believe in the possible existence of another periodicity with a lesser number of years. Let us assume, therefore, that in this case there may be consecutive periodicities of from 3 to 15 years inclusive.

Our next step is to draw up a table: average yearly, average for May months, average for September months, and the levels for September lst, all listed as following: three columns (a three-year periodicity), then four columns (4-year periodicity), and so on up to 15 columns for a 15-year periodicity. For our example we present only two of the tables, viz., for the 8-year periodicity according to the September 1st levels (Table 15) and for the 11-year periodicity, also based on September 1st levels (Table 16).

We add up the figures in the columns of each table and arrive at the maximum and minimum sums and find the differences between them. In Table 15 this difference amounts

Table 15

Ground Water Levels
on the 1st of September of Each Year

	58.66	59.68	59.90	59.70	60.47	60.96	60.54	60.45
	58.50	59.00	59.05	58.58	58.49	60.37	61.17	61.71
	61.72	61.11	60.72	60.19	60.17	60.09	59.58	61.56
	61.64	61.96	61.61	62.15	61.47	60.10	59.79	59.31
	58.87	58.56	60.43	60.84	61 17	61.47	60.38	59.86
	60.17	60.57	59.99	59.23	58.84	59.12	58.61	58.39
Total:	359.76	360.88	361.70	360.69	360.61	362.11	360.07	361.28

to 2.35, while in Table 16 the corresponding difference is 7.96.

The largest sum is 362.11; the smallest is 359.76. The difference is 2.35.

The largest sum is 305.56; the smallest is 297.60. The difference amounts to 7.96.

Table 16

Ground Water Levels on the 1st of September of Each Year

58.66	59.68	59.30	59.70	60.47	60.96	60.54	60.45	58.50	59.00	59.05
58.58	58.49	60.37	61.17	61.71	61.72	61.11	60.72	60.19	60.17	60.09
59.58	61.56	61.84	61.96	61.61	62.15	61.47	60.10	59.79	59.31	58.87
58.56	60.43	60.84	61.17	61.47	60.38	59.86	60.17	60.57	59.93	59.23
58.84	59.12	58.61	58.39	58.93	60.35	62.12	61.46	60.85	60.78	60.36
Total: 304.22	299.28	301.56	302.39	304.19	305.56	305.10	302.90	299.90	299.25	297.60

A diagram is then drawn, and on the axis of the abscissae we mark off the periods for which tabular computations have been made, while on the axis of the ordinates and to a predetermined scale we record the differences of the sums (maximum and minimum). Fig. 54 shows such a diagram for the Kamennaya Steppe.

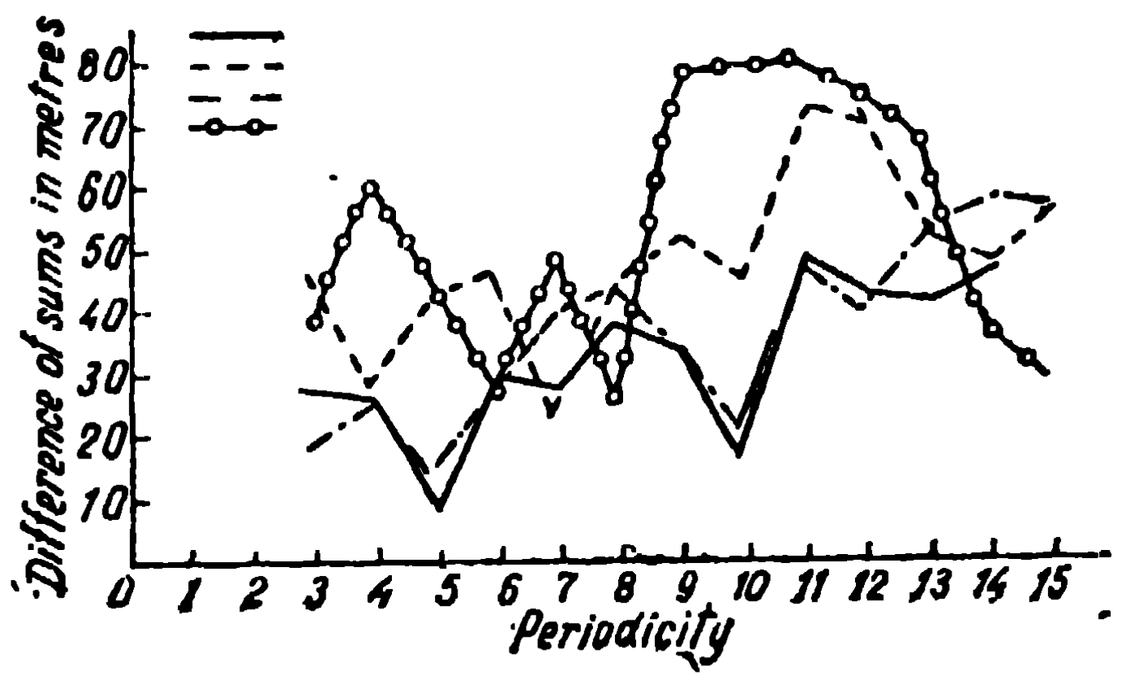

Fig. 54 Periodicity diagram (Kamennaya Steppe, well No. 1).

1—average annual levels; *2*—average levels for the months of May; *3*—average levels for the months of September; *4*—levels of 1/IX of each year.

This diagram illustrates periodic fluctuations in differences between each pair of sums: average annual levels, average levels for the months of May, the same for September, and also for September 1st of each year.

The diagram definitely indicates periodicity in fluctuations of the level of ground waters.

It is well to remember that from the very essence of the periodogram method, the assumption of periodicity will be true for that difference which is greatest. On the diagram these differences are expressed by corresponding peak values.

From Fig. 54 it follows that the maximum difference of sums for different levels corresponds to 9, 10, 11 and 12 years. It is impossible to accept the 9-, 10- and 12-year perio-

dicities since the maximum difference of the sums for these years may be observed only by taking the September 1st levels of each year. Average annual levels, as well as average monthly levels for the months of May and September show that both to the left and right of the 11-year period the difference of sums is less. Consequently, periodicity should be equal to 11 years.

In the interval from 4 to 9 years the difference of sums is extremely variable but in all cases it is below 11 years. Hence, periodicities of 4, 5, 6, 7, 8 and 9 years are non-existent.

If we assume that the lines representing average annual levels and average levels for the months of May show an increase in the difference of sums for three consecutive years, then we may suppose that there is also a not very pronounced three-year periodicity.

It should be noted in conclusion that when determining periodicity, the absolute magnitude of peak values of the difference between the sums is not essentially important, the greatest criterion being the sharply pronounced nature of the peaks and the minimum value of the difference between the sums to the right and left.

6. APPROXIMATE METHODS OF FORECASTING UNDERGROUND WATER REGIMES

Approximate forecasting methods are based on the collection and systematization of regime observation data, and analyses and coordination of information pertaining to geological structure and hydrogeological conditions of a given territory. To use this method, a study of natural environment and the establishment of factors affecting the underground water regime must be made.

Such approximate methods will disclose the general trend of processes taking place in the aquifer. The work involves a number of years of study by a frequent network of observation points; during this work the territory is divided into hydrogeological sectors in order to study the underground water regime in each division. Forecasting must be preceded by careful processing, analyses and systematization of

formation relating to the geology and hydrogeology of the region and of data on the regime of underground waters.

Up to the present these methods have been used only for forecasting fluctuations in levels and discharges, though they may be also applied to forecasting changes in the chemical composition and temperature of the waters.

Approximate methods may be employed both for long- and short-term forecasts.

The methods are divided into: a) simple forecasts and b) method by analogy.

Simple forecasts are made on the basis of: a) charts showing fluctuations in level, discharge, temperatures and chemical composition of underground waters observed at individual points or at groups of points; b) analyses of diagrams and maps of the underground water regime of a given territory; c) data derived from the exploitation of sources of underground water.

The method by analogy is applied for a territory whose regime of underground waters has not yet been investigated; this method involves the use of information available for regions with similar hydrogeological, climatic and other conditions.

A brief description of each of these methods is given below.

A) SIMPLE FORECAST OF UNDERGROUND WATER REGIMES

The most elementary type of forecast of underground water regimes consists in the compilation of bulletins based on many years of observation. When the regime at one or a group of points is investigated for a long period (several years) the nature of fluctuations of levels, and the chemical and temperature variations of the water may be established. Maximum and minimum levels, their dates and features peculiar to such variations in the course of the year will be disclosed by the use of diagrams illustrating underground water regimes at each observation point. The same may be said with regard to the study of spring discharges or flowing wells.

The same procedure is employed for approximate qualitative forecasts of variations in temperature or chemical composition of underground waters.

To effect an approximate forecast it is necessary to establish not only the laws governing annual variations, but

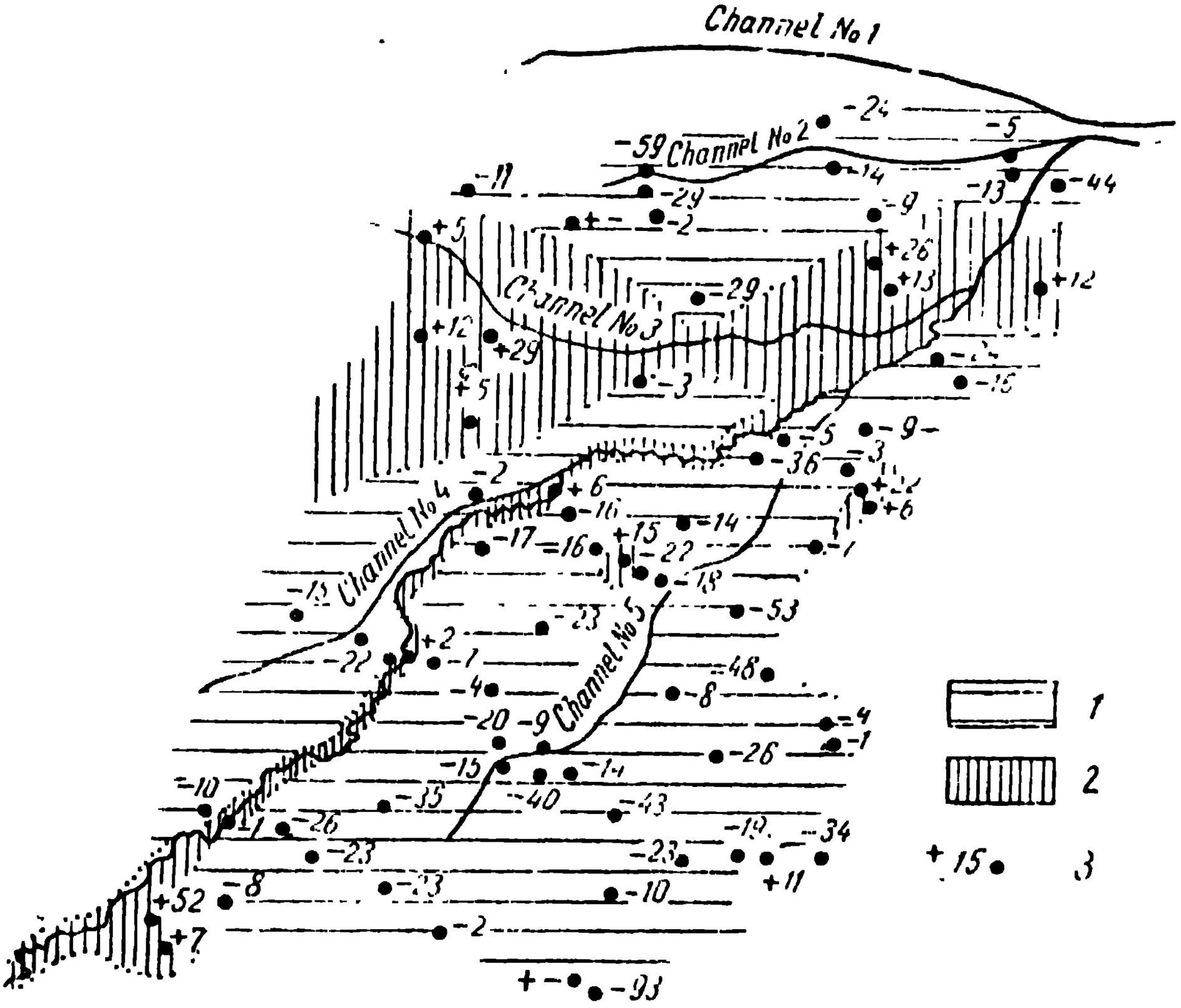

Fig. 55. Scheme of water table in an irrigated region of Central Asia, for comparison with a preceding year.

1—areas of falling water table; *2*—areas of rising water table; *3*—observation well indicating a fall (—) or a rise (+) of the water table in cm.

also those affecting fluctuations over periods of many years; for it has been found that aside from seasonal fluctuations, there also exist rhythmic undulations in level over a number of years. Periods of fall and rise are generally similar in various hydrological sectors but differ in range.

When forecasting the regime for an aquifer a detailed inquiry should be made of the geological structure and hydro-

geological conditions of the given territory, and the region divided into hydrogeological divisions.

A comparison of diagrams showing fluctuations in level, chemical composition and temperatures of the water, togeth-

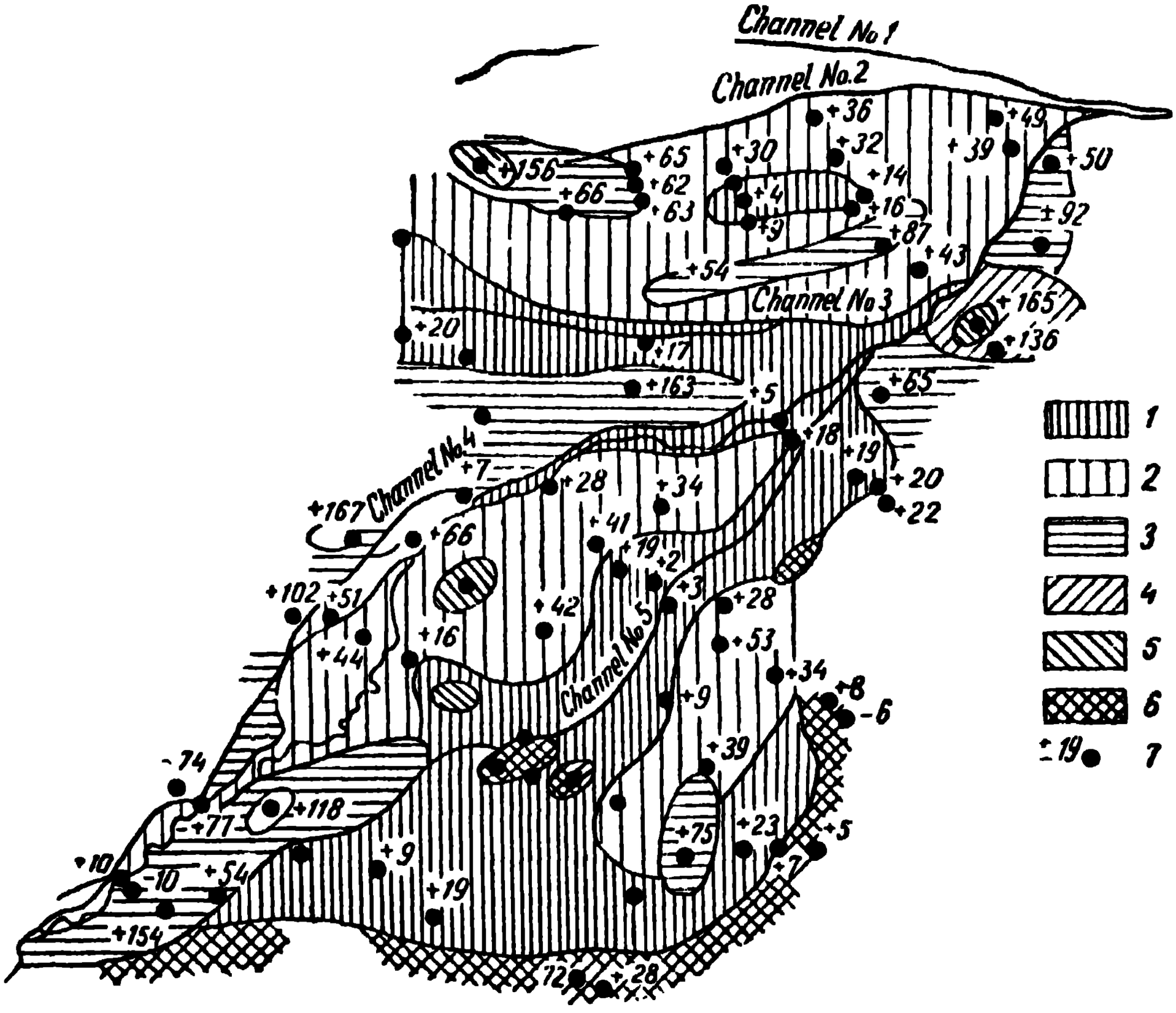

Fig. 56. Scheme of water table in an irrigated region of Central Asia in March of the given year as compared with that of March of the preceding year.

The position of the water table in March of the given year is higher than in March of the preceding year: *1*—from 0.01 to 0.25 m.; *2*—from 0.25 to 0.50 m.; *3*—from 0.50 to 1.00 m.; *4*—from 1.00 to 1.50 m.; *5*—from 1.50 to 2.00 m.; *6*—the position of the water table in March of the given year is lower than in March of the preceding year by from 0.01 to 0.30 m.; *7*—observation well indicating a drop (—) or rise (+) of the water table.

er with a parallel consideration of the natural historical environment of observation points will reveal the general laws peculiar to any group of such points. A classification of regime types and a subsequent detailed subdivision of the territory under study should be effected only after careful

consideration of geological and hydrogeological conditions prevailing at these points.

Analysis of diagrams is insufficient for forecasting the ground water regime in individual areas; to this must be added the compilation of special maps.

Such forecasts as described above have been made by certain hydrogeological stations studying ground water regimes for irrigation. One such station employed a very ingenious forecasting method (during the exploitation of sources of confined waters) by determining the relationship between level fluctuations and pumped water.

The quantity of water delivered to the field is the principal factor governing the regime of underground waters in irrigated regions. A surplus stimulates a rise in ground water level and leads to swamping and salinization of the soil and to an increase in total mineralization of ground waters. With the purpose of inquiring into this process and thus preventing harmful after effects, some hydrogeological stations prepare maps showing changes of the ground water table in such regions. Maps of the current and previous year are compared, comparisons being made, for example, of variations in ground water level and chemical composition due to soil washing (the maps having been compiled for definite dates and at the ends of soil washing seasons).

We have presented some examples of such schematic charts prepared by E. N. Doich.

An examination of the first chart will show that in contrast to the preceding year, a rise in water level occurred in the region of channel No. 3, while a marked drop was registered for the remaining territory (Fig. 55). A comparison of the quantity of water delivered in the course of the two years under survey made it evident that in the year when the map was compiled, channel No. 3 received a considerably greater amount of water than in the previous year. Such an analysis, particularly if information is given for several preceding years, will furnish the basis for an approximate forecast of a regime for the forthcoming year, supply material for recommendations of rates of water delivery, and furnish the basis for planning adequate drainage.

Of no less interest is Doich's map for March of the preceding and current years (Fig. 56); here areas are shown with

ground water rises comprising from 0.01 to 0.25 m., from 0.25 to 0.50 m., from 0.50 to 1.00 m., from 1.00 m. to 1.50 m., from 1.50 to 2.00 m., as well as districts where the level declined in March. This chart made it possible to foresee

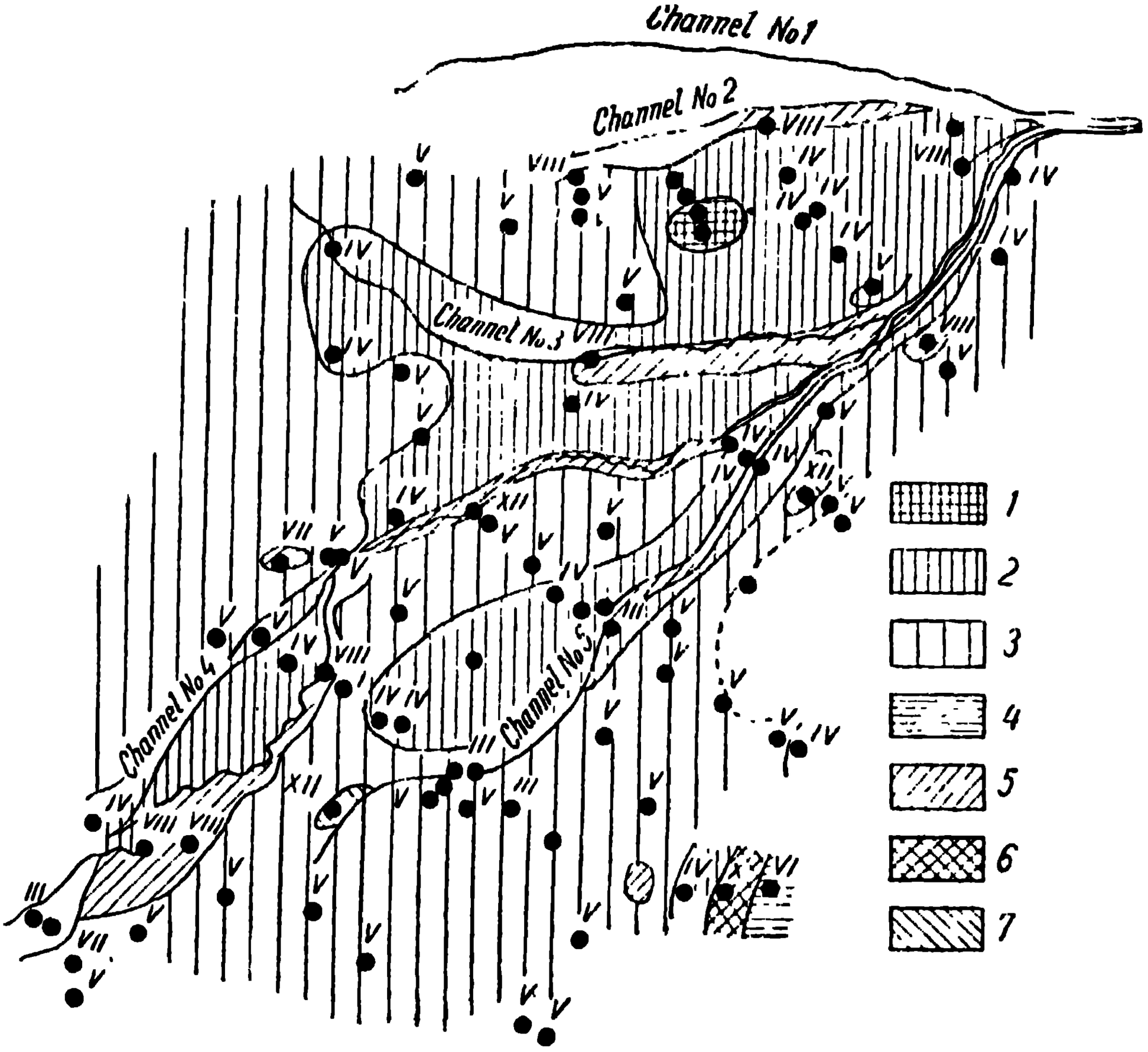

Fig. 57. Scheme of areas characterized by a simultaneous maximum position of the water table in an irrigated region of Central Asia.

The maximum was observed: *1*—in March; *2*—in April; *3*—in May; *4*—in June; *5*—in August; *6*—in September; *7*—in December.

level changes for the immediate future, i. e., to give short-term forecasts and also to regulate the underground water regime.

It is likewise desirable to compile a chart showing the location of areas with simultaneous maximum levels of ground waters in irrigated region during preceding years (Fig. 57).

Compilation of these maps requires a detailed study of the hydrogeology of the region, determination of principal factors governing the regime of underground waters, and organization of meteorological and hydrometric observations.

To forecast chemical changes of underground waters maps are drawn up for comparing chemical composition of the

Fig. 58. Variation curves of the water level in a borehole and the yield of water.

1—water level in bore A; *2*—yield (summarized).

water for corresponding seasons of the current and preceding years.

In a certain region where confined water was being exploited, a study of the regime in many of the wells located at relatively short distances from each other caused certain disclosures; a sharp fall in piezometric surface was taking place because of the dependence of the level upon intensity of water withdrawal. This decline might have led to the failure of a number of active wells. But measures based upon correct observations of the regime of the aquifer under exploitation prevented possible harmful consequences.

In another instance a field investigator (A. M. Fedorova) organized regular observations of the piezometric surface in a number of exploited and closed wells and observation bores. A simultaneous gauging of water discharge was carried out periodically in all active wells.

Subsequent compilations of diagrams and analyses of variations in the piezometric surface established a direct relation between fall in level and the drawing of water. Isopiestic lines plotted at different dates and analyses of the said diagrams permitted a regional division of the territory according to the underground water regime. Diagrams were compiled for each division showing the relation between variations of the piezometric surface and the volume of water drawn (Fig. 58).

The employment of these regional diagrams, together with a due consideration of the planned quantity of water withdrawal made it possible to give an approximate forecast of level variations for various periods of the year and to regulate the drawing of water with the aim of retaining a definite piezometric level. These observations and forecasts rendered a great service to the national economy.

From all this it is clear that forecasting requires systematic observation of the behaviour of the level of underground waters and the establishment of a principal factor to determine typical features of the regime. In the case described above such a principal factor proved to be the exploitation of the water-bearing horizon.

B) FORECASTING THE REGIME OF UNDERGROUND WATER BY THE METHOD OF ANALOGY

This method is mostly employed when a prognosis of the underground water regime is required before an accumulation of long-term forecast data can be completed.

In such a case it is very important that a detailed study be made of the region's geological structure and hydrogeological conditions and that data be gathered concerning the climate of the territory and its hydrometry.

The preparation of such a forecast presupposes the availability of normal information on long-term observations

of underground water regimes in another region with similar geological structure and hydrogeological and meteorological conditions.

Surveys of level fluctuations of ground waters in an extensive Central Asian and a Southern Kazakhstan region have established the existence of rhythmic changes over a period of many years.

A study of ground water regimes conducted by hydrogeological stations located in areas with different natural conditions had proven the following:

1. Together with seasonal changes in elevation of ground waters and discharge of springs, there also exist long-term variations of the same type under unlike hydrogeological conditions (in regard to time of high and low levels and discharges) but differing in amplitude;

2. Long-term natural variations in the regime of underground waters are determined by climatic factors (precipitation, evaporation, etc.) and by the water discharge of rivers whose feed intensity is dependent largely upon hydrogeological conditions;

3. As a rule, long-term variations of climatic factors conform with the regime of surface run-off;

4. Long-term variations of the ground water table may be affected by artificial factors. Sharp deviations in the general course of natural fluctuations of the water table under the influence of artificial factors occur only over relatively small areas, while on extensive territories the influence of these factors is limited to an increase or decline in the amplitude of natural fluctuations, with no disruptions in the sequence of their general course.

Hence the method of analogy may be used for foretelling time variations of level and discharge of ground waters not only for one year, but the general trend of the process may be predicted for many years.

7. THE CORRELATION METHOD

The accumulated data obtained by hydrogeological stations in their observations over a period of years will allow them to apply the correlation method for the processing of data and forecasting of underground water regimes.

It should be noted before explaining this method that there are exact and inexact dependencies between variables. Examples of exact dependoncies or correlations are mathematical or other formulae, where only one and the same value of a dependent variable always corresponds to a definite value of an independent variable. For example, in the formula expressing the discharge of an underground flow $Q=F\cdot K\cdot I$, the resultant value of the dependent variable Q is always the same at definite values of the independent variables F, K and I although it may not be exact due to an insufficiently precise determination of the values F, K and I.

In inexact dependencies it is not the strictly definite value of a dependent variable that corresponds to a definite value of an independent variable, but its mean value from which the true or actual value differs by one or another quantity. For example, given an inexact dependency between the level of ground water and the amount of precipitation expressed by the formula $x=2+4y$ when $y=2$, we obtain the mean value of x which is equal to 10. But the actual level of ground waters in individual wells will differ from this mean figure by some other value. This is because inexact dependencies do not express the relationship of all factors exercising their influence over the value under investigation, but merely between the latter and one or several basic factors. In the case discussed here, although the mean value of the level is related to only one factor—precipitation, it depends not on precipitates alone, but on a number of other factors not taken account of in this relationship of meteorological factors (evaporation, temperature, etc.).

The method of correlation enables us to find inexact relations and to express them analytically in the form of a formula giving a mean value for the quantity sought. This method should find widespread application in processing the material obtained from regime observations and in forecasting the regime of underground waters. The number of problems from the field pertaining to the study of underground water regimes which can be solved by the correlation method is exceedingly large and depends upon available facts and the duration of observations.

Work related to the establishment of correlated depend-

encies should begin chiefly with an investigation of the natural processes themselves, disclosure of general laws characterizing their course within natural environments, and finally with the revealing of the principal natural or artificial factors affecting one or the other element of the regime of underground waters. These usual preliminary hydrogeological analyses will eliminate a purely mechanical utilization of the correlative method, ensure a correct approach to the problems, and successfully establish correlated dependencies with the highest possible accuracy. Some examples are given below to illustrate this.

Let us assume that we desire to obtain correlated dependencies which would allow us to determine the level of ground water in a forthcoming month on the basis of its average position during a preceding month; for example, on the basis of its level in May to determine that in June, or to obtain the July level on the basis of the June level, etc. The question first arises whether this problem could be solved for all 12 months of the year. To decide this let us follow the general course of variations in the level of ground waters during the entire year and investigate their underlying causes. We are aware that in regions with a stable snow cover the level of ground water will show a sharp rise around the month of May and then gradually fall until the autumn months (September-October) and sometimes even until the winter months (February-March). It is known that the gradual decline from the maximum level in May finds its explanation in the outflow of ground waters and in the lack of their intensive replenishment through atmospheric precipitates during the summer.

It therefore follows that from May to October (or from May to March) both the course of variations in the level of ground waters and their causes are quite clear (chiefly through drainage into the hydrographic system). This ensures in advance the establishment of an adequate correlated dependency for the given months with an accuracy sufficient for practical purposes.

But it is a different matter for the period involving a sharp rise in level (March-May). Here a reverse process takes place, consisting essentially in the recharge of ground waters. But recharge and, consequently, the character of a rise in level

is subservient to many factors whose degree of influence is not sufficiently clear. A big role is acted here by temperature changes (in air and soil), rainfall, intensity of snow melting, frost in the ground, and the nature of the vegetative cover. All these factors are in a measure conducive to an uneven rise, differing from year to year, in the spring level of ground waters. But such conditions suggest in advance that correlated dependencies are either altogether unattainable or will be marked by a high degree of inaccuracy. Hence some other ways of solving the problem must be looked for; these will be discussed in detail below.

Let us now examine the annual underground level fluctuations in regions devoid of a stable snow cover (as for instance the Crimea and Central Asia). In these regions recharge is achieved during the autumn and winter period through atmospheric precipitates and frequent thaws. Under such circumstances the rise in the level of ground waters during this period assumes a more or less gradual character. Consequently, the year may be split into two periods corresponding to a drop and a rise in level. The decline in level occurs chiefly because of drainage, while the upward movement may be mainly ascribed to recharge through precipitation. The result is that it is possible to compile two correlated dependencies: one for the period of decline and the other for the period of rise in the ground water level. From this it follows that a hydrogeological analysis warrants both a correct approach to the general problem of the correlation method and its division into separate parts.

Now let us return to the annual course of fluctuations in the level of ground waters in regions possessing a stable snow cover. We have pointed out earlier that a correlated dependency for the period of falling level should be sought for only during May-October or May-March. During these periods the intensity of fall in the level will differ for different years. A dry summer and a big moisture deficit in the air will intensify the lowering of the water table, while a relatively wet summer will retard the fall-off in level. Hence the results of observations will not be the same for each year and it is therefore recommended that all such data concerning variations in level during the May-March period be divided into three groups: one—for a fall in ground water level during years

with dry summers, another for those with wet summers, while the third should pertain to years whose summers are of average precipitation. Such a grouping will facilitate the computation of three correlated dependencies.

But at this point a question arises: which of these three correlated dependencies should be chosen in forecasting the level of ground waters for the approaching summer? The answer depends upon which of two types of forecast bulletins it is intended to issue. If the ground water prognosis given in May is to simultaneously embrace all subsequent summer and autumn-winter months, then the selection of one of the three correlated dependencies should be based only on the weather forecast for the forthcoming summer-autumn period as furnished by the Hydrometeorological Service of the U.S.S.R. On the other hand, if it is intended that forecasts of a sinking level of ground waters are to be given monthly, i. e., that bulletins are to be printed in May for June, in June for July, and so forth, then the amount of precipitates for each preceding month will be known and it will be clear which of the three correlated dependencies is to be employed.

A network of hydrogeological stations studying ground water regimes very often covers diverse geomorphological areas. Furthermore, on individual plots a water-bearing strata may be made up of unlike lithological varieties of rock and it is therefore natural that the lowering of the ground water table during the summer-autumn period will vary according to these conditions. Such considerations permit a new grouping of observation data in order to arrive at new, more precise correlated dependencies. If a hydrogeological station is in possession of sufficient information based on long surveys of the various geomorphological elements of the territory and of differing lithological types of water-bearing layers, it can establish a number of correlated dependencies which would not only take account of the quantity of summer precipitation, but also of the territory's geomorphology and its lithology of water-bearing strata.

Correlated dependencies for a lowered summer-autumn level may be computed if there is a sufficiently detailed and correct grouping of survey data, as for example—in the

coarse sands of an upper floodplain bench during dry summer years, in coarse sands or pebble beds of valley trains in years of wet summers, etc.

We have already said that forecasting of a ground water level for a spring rise period is hardly possible if available information covers only the preceding month, and that some other means must be sought to solve this problem. The basic cause of a rise of ground water levels in the spring should be determined firstly. This problem cannot always be decided beforehand for all times or all conditions and requires certain assumptions; several correlated dependencies must be deduced and one selected which will be distinguished by its highest degree of accuracy or by its highest correlation coefficient. For example, it might be assumed that the rise in the level of ground waters is dependent upon the amount of rainfall in the autumn. But for regions with a stable winter snow cover this assumption is obviously wrong and it is useless to seek for a correlated dependency between them. Two other suppositions may be advanced: that the rise in level of spring ground water is dependent upon: a) snow reserves per unit of area; b) depth of the frozen ground or, more precisely, moisture reserves in a solid state in the zone of seasonal freezing. Both assumptions are quite probable and two correlated dependencies should therefore be found with the subsequent adoption of the one possessing the highest correlation coefficient. Thus, the method of correlation not only makes it possible to arrive at a correlated dependency, but is helpful in determining the basic factor influencing any given element of the water regime.

Correlated dependencies may be found between the level of underground waters and any other natural or artificial factors. For example, a relation may be established between amount of precipitates, evaporation losses, water levels in rivers, reservoirs and canals, the quantities of irrigation and pumped water, etc. But it should be borne in mind that the correlated dependency should be looked for between the given element of the regime and the basic factor, the latter being chosen from among those which precede the changes in the given element of the underground water regime. For indeed, although there is no doubt of a relation between precipitation and a shallow layer (i. e., near the ground sur-

face) of phreatic water occurring in pebble beds (for the ground water level rises almost immediately following precipitation), any attempt to find a correlated dependency in this case would be inexpedient because an advance knowledge would be required of definite dates and amounts of rainfall in order to forecast the ground water level; this is hardly possible in practice. On the other hand, if the influence of precipitation on the level of ground waters makes itself felt after a certain length of time, the establishment of a correlated dependency between level and precipitation is possible and desirable.

The above examples quite clearly indicate the way in which problems should be formulated in order to apply the correlated method and how available facts should be grouped. Let us now demonstrate the method itself through a concrete example.

Let us assume that we must evaluate the accuracy of the relation between the levels of a preceding and following months and establish a correlated dependency between them; x will denote the levels of ground waters for a preceding month, y — for those of a following month. Properly selected and grouped data should be listed in a table and a graphic relation found between the levels of ground waters under survey. Let us assume that Table 17 is our available data from observations of ground water levels.

We then construct a line graph and on the axis of the abscissae we mark off level intervals (for example, 10 cm.) for

Table 17

Borehole Nos	May	June	July	August	September	October
1	105	68	4	31	13	11
2		96	61	27	21	15
etc.						

Note: levels of ground waters should be marked off in cm. from an optional zero-mark placed lower than the minimum level of ground waters over a long range of years.

the preceding month and on the axis of the ordinates the levels for the forthcoming month (Fig. 59). In well No. 1 the level in May (the preceding month) was 105 cm. above the zero-mark, and 68 cm. in June (the following month). With these figures as a basis we plot a point on the graph $x = 105$ cm. and $y = 68$ cm. (point *1*, Fig. 59). The coordinates of the next point will be $x = 68$ cm. (preceding month—June) and $y = 45$ cm. (the following month—July) (point *2* in Fig. 59). Thus we consecutively plot on the diagram all the data contained in Table 17, designating the points separately for each well by different conventional signs.

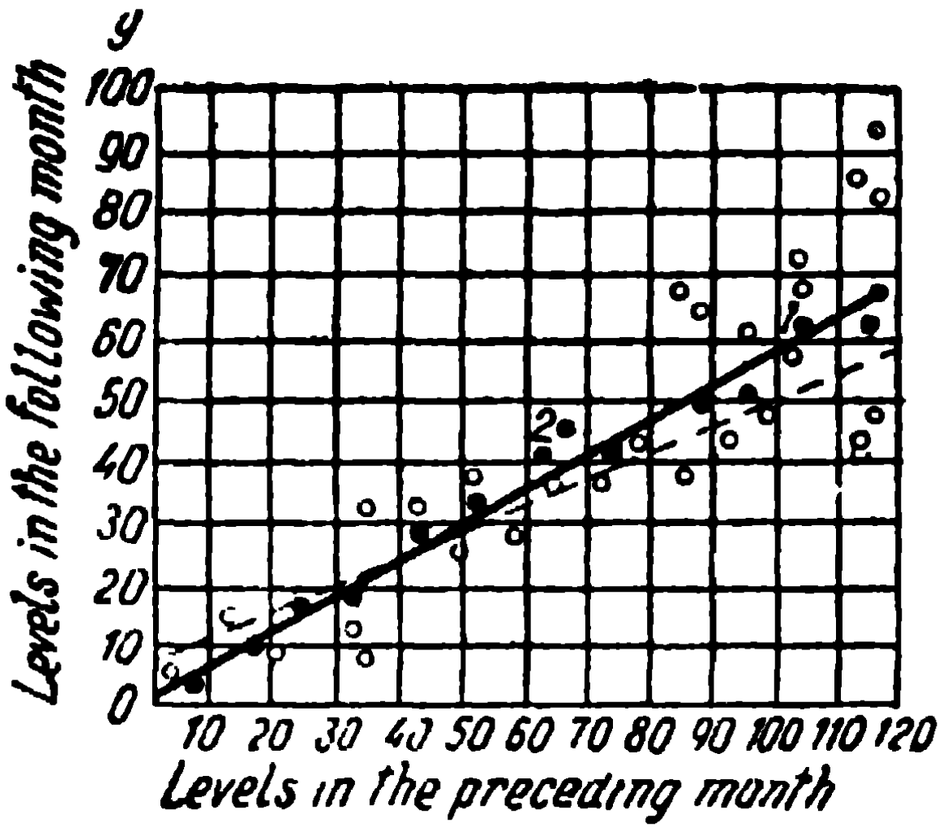

Fig. 59. Correlation of water level in a preceding and following months.

Let us now calculate the relation between x and y. For this purpose we divide the line graphs into vertical bands which include equal intervals of the value x, and into horizontal bands which include equal intervals of the value y. For example, the first vertical band will include the values of x from 110 to 120, the second one—from 110 to 100 and so on. We then compute the mean value of x_0 and y_0 separately for each vertical horizontal band as an arithmetical mean of all values for the level of ground water included in any particular band. For example, the first band contains 8 points with the following numerical values: 92, 90, 85, 70, 55, 48, 46 and 42. The mean value y_0 for this band is equal to 66, while for the coordinate x the mean value of the interval is from 110 to 120, i. e., 115. On the basis of the above we plot a black dot on the diagram. Similar computations are made for the other vertical bands. From the results thus obtained we plot points (circles, Fig. 59) on the diagram for all vertical bands whose coordinates have corresponding mean values of y_0 and mean values of the intervals of x. Through these points we draw a straight thick line (Fig. 59). The same operation having been con-

ducted for the data contained in the horizontal bands, we arrive at the mean values for x_0 which we then place at the mean value of the intervals y. We then again draw a straight line (this time dashed— Fig. 59).

As a result we arrive at two linear relations: y_0 from x, and x_0 from y, i. e., mean values for the level of ground waters for the forthcoming month obtained from its given values in the preceding month, and mean values of the preceding months from the given values in the following months.

An examination of Fig. 59 will reveal that the points are distributed regularly along a definite diagonal band and that a definite value of y fluctuating in the proximity of a certain mean value corresponds to each value of x. The existence of two separate straight lines signifies that we have arrived at inexact dependencies, since both straight lines would have merged for an exact dependency. On the other hand, in the absence of any relation between the values x and y the points on the diagram would have been distributed very much at random. Therefore, between the absence and existence of an exact relation there is a series of inexact dependencies whose degree of accuracy or inaccuracy may acquire diverse values.

To determine the degree of accuracy of the relation between values under investigation in the correlation method, a correlation coefficient is introduced. To demonstrate the substance of this coefficient we will transfer the origin of the coordinates to the point of intersection of both straight lines shown on Fig. 60 and will denote by α the angle of slope of the straight line y_0 to the axis of the ordinates, and by β the angle of slope of the straight line x_0 to the axis of the abscissae (Fig. 60). It is obvious that the greater the divergence between the lines I and II, the less accurate will the relation be between x and y. The correlation coefficient is expressed by:

$$r=\sqrt{\operatorname{tg}\alpha+\operatorname{tg}\beta} \qquad (14)$$

If there should be no relation, the straight lines I and II in Fig. 60 will show a maximum divergence and ultimately will merge with the respective axis of the coordinates (the

straight line I with the axis y, and the straight line II with the axis x). With the straight lines in such a position $\alpha=0$ and $\beta=0$, and hence the correlation coefficient will also be equal to zero. Conversely, in the presence of an exact relation, both straight lines will merge. In this case the angle is equal to $90°-\beta$, $\alpha=\text{tg}\ (90-\beta)=\text{ctg}\ \beta$.

Hence

$$r=\sqrt{\text{tg}\alpha+\text{tg}\beta}=\sqrt{\text{ctg}\beta+\text{tg}\beta}=1.$$

Therefore, in exact relations the coefficient of correlation will be equal to 1. The correlation coefficient may have a positive or a negative value. In the first instance this will signify that with an increase in the value of the first variable, the second will also augment. And, conversely, a negative value of the coefficient of correlation will point to an inverse relation, that is, the greater the value of one variable, the less will be that of the other.

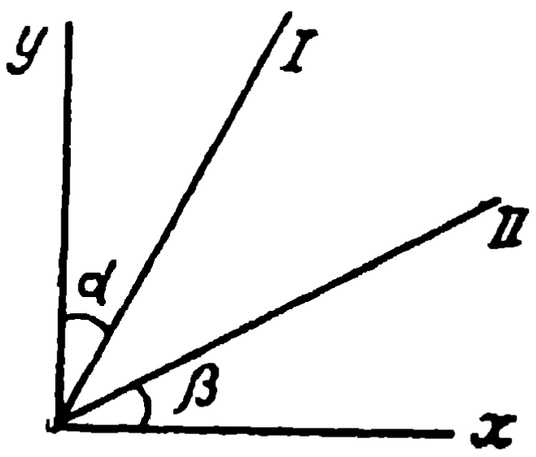

Fig. 60.

The computation of the correlation coefficient and the establishment of correlation dependencies is conducted with the aid of correlation tables compiled in the following manner. Firstly a graph is drawn similar to the correlation graph. Then the intervals for the y values (the levels of ground waters during the following month) are written into each horizontal line in the extreme left column, and the intervals for the values of x are noted at the top (levels of ground waters during the preceding month) (Table 19.) The table is thus divided into a number of separate squares, corresponding to definite values of the intervals x and y. For our purpose the interval for variations in the level of ground waters is taken as 10 cm. Therefore, in the extreme left column (from the bottom upwards) the intervals for the values of y will be 0 to 10, 10 to 20, etc., while the upper squares (from left to right) will indicate the intervals for the values of x, likewise 0 to 10, 10 to 20, etc.)

Then, instead of the numerical values of ground water levels given in Table 17, we mark into individual squares of the correlation table the points indicating the interval

to which any given numerical value of the ground water level belongs. For example, according to the level recorded during May (preceding month) in well No. 1 the value x=105 cm., while according to that of June (following month) the value y=68 cm. We therefore mark down the point in the square that corresponds to the interval of 100 to 110 x and to the interval 60 to 70 y. The points are marked in the same manner for all the months and all the wells. Since the points in individual squares will be summed later, it is advisable to adopt a certain order of marking when there is a large number of points: triangles for 3 points, squares for 4 points, etc.

After the points have been placed in the correlation table we begin calculating the mean values of y_0 and x_0 for corresponding intervals of x and y in the way described before, i. e., by taking 5, 15, 25, etc., as the mean values of the intervals of x and then calculating the mean value of y for all points contained firstly in the interval from 0 to 10, then from 10 to 20, and so on. For example, the interval of the values 110 to 120 x contains eight values of y, the mean value being equal to 66. The result is another table containing the mean values of the intervals x and y and corresponding to the mean values of x_0 and y_0 within the limits of these intervals (see Table 18).

Table 18

Mean value of the interval x (level for the preceding month)	Mean value of y_0 in the given interval x (mean value of level for the following month)	Mean value of the interval y (level for following month)	Mean value of x_0 in the given interval y (level for the preceding month)
5	3	5	6
15	8	15	9
25	12	25	12
35	23	35	14
etc.	etc.	etc.	etc.

Then six columns are appended to the right of the correlation table, and six lines affixed below as shown in Table 19.

y \ x	0—10	10—20	20—30	30—40	40—50	50—60	60—70	70—80	80—90
100—90									
90—80									
80—70						•			
70—60									••
60—50									
50—40							•	•	
40—30				•	•	•	•	•	••
30—20			•		•	•			
20—10		••	•	•••					
10—0	••	•	•						
I n_x	2	3	3	4	2	2	2	2	4
II x_1	—5	—4	—3	—2	—1	0	+1	+2	+3
III $n_x x_1$	—10	—12	—9	—8	—2	0	+2	+4	+12
IV $x_1[n_x x_1]$	50	48	27	16	2	0	2	8	36
V $[\Sigma x_1]$	—8	—10	—9	—10	—3	—9	—1	—1	+2
VI $x_1\ [\Sigma x_1]$	+40	+40	+27	+20	+3	0	—1	—2	+6

Table 19

			I	II	III	IV	V	VI
90—100	100—110	110—120	n_y	y_1	$n_y y_1$	$y_1 [n_y y_1]$	$[\Sigma y_1]$	$y_1 [\Sigma y_1]$
		•	1	+5	5	25	+6	+30
		••	2	+4	8	32	+12	+48
	•	•	2	+3	6	18	+11	+33
•	•		4	+2	8	16	+15	+30
	•	•	2	+1	2	2	+11	+11
••		•••	7	0	0	0	+29	0
			7	−1	−7	7	+6	−6
			3	−2	−6	12	−4	+8
			6	−3	−18	54	−17	+51
			4	−4	−16	64	−17	+68
3	3	8	38		−18	+230		+273
+4	+5	+6						
+12	+15	+48	+52					
48	75	288	+600					
+2	+6	+17						
+8	+30	+102	+273					

In column I, line I, denoted by n_y and n_x, the number of points contained in the intervals y (the lines of the table) and in the intervals x (the columns of the table) are summed up. For example, one point is marked down in column I-n for the interval 100 to 90 y, seven points are taken for the interval 50 to 40, four points—from line I for the interval 30 to 40 x. In column II, line II, denoted by y_1 and x_1, we mark down sequence symbols, their approximate average being taken as the zero interval. The interval from 40 to 50 is taken as the zero interval in column II, and that from 50 to 60—in line II. Sequence numbers of the plus-intervals are marked into column II above the zero interval, while the sequence numbers of the minus intervals go below the zero interval. Minus intervals are placed to the left in line II, while those with the plus-sign are placed to the right.

The results of multiplying the figures in column I (line I) by those in column II (line II) are then put down in column III and line III, denoted by $n_y y_1$ and $n_x x_1$.

The results of multiplying the figures in column II (line II) by those in column III (line III) are written in column IV and line IV as denoted by $y_1[n \cdot y_1)$ and x_1 $[n_x \cdot x_1]$.

In the column V, designated by $[\Sigma y_1]$, we write the sum of the sequence numbers of intervals indicated on the line for all points contained in the given interval y, while on line V, denoted by $[\Sigma x_1]$, we write the sum of sequence numbers of intervals indicated in column II for all points contained in the given x interval. For example, in column V the figure $+29$ was arrived at in the following manner: there are altogether 7 points in the interval of the values y from 40 to 50: three of them are in the interval x from 110 to 120, and this interval (on line II) has a sequence number of $+6$. Hence the sum of sequence numbers for all of these three points should be equal to $6+6+6=18$. Then in the same 40 to 50 y interval there are two points (in the 90 to 100 x interval), for which the conventional sequence number on line II is equal to $+4$, therefore their sum should be equal to 8. And, finally, in the y interval there is one point whose value, according to the sequence number of the interval on line II, is equal to $+2$, and another with the value of $+1$. The total sum of all values enumerated above is equal to 29 and this latter figure is marked down in column V. The figure -1 in line V is

arrived at by adding the values of sequence numbers of the interval in column II for two points —1 and zero. In column VI, line VI, designated by $y_1[y_1]$ and $x_1[x_1]$, we write the results of multiplying the figures in column II (line II) and the figures of column V (line V).

And finally we add up the figures marked down in all columns and all lines, excepting columns II and V (lines II and V), the sum of column VI being equal to the sum of line VI. The sums of all columns and lines are denoted as follows:

The sum of the column	I,	line	I	by Σn	(38)
„ „	„	III	„	III by $\Sigma n_y y_1$ and $\Sigma n_x x_1$	(—18 and +52)
„ „	„	IV	„	IV by $\Sigma y_1[n_y y_1]$ and $\Sigma x_1\ [n_x x_1]$ and +600)	(+230
„ „	„	VI	„	VI by Σxy	(+273)

The correlation table thus compiled will enable us to compute the correlation coefficient and to determine a correlated dependency.

The correlation coefficient will be equal to

$$r = \frac{\frac{\Sigma xy}{\Sigma n} - v_1 \cdot v_2}{\delta_y \cdot \delta_x} \qquad (15)$$

where:

$$v_1 = \frac{\Sigma n_x \cdot x_1}{\Sigma n} = \frac{52}{38} = 1.368;$$

$$v_2 = \frac{\Sigma n_y \cdot y_1}{\Sigma n} = \frac{-18}{38} = -0.474;$$

$$\delta_y = \sqrt{\frac{\Sigma y_1 [n_y \cdot y_1]}{\Sigma n} - (v_2)^2} = \sqrt{\frac{230}{38} - (-0.474)^2} \cong 2.41;$$

$$\delta_x = \sqrt{\frac{\Sigma x_1 [n_x \cdot x_1]}{\Sigma n} - (v_1)^2} = \sqrt{\frac{600}{38} - 1.368^2} = 3.78;$$

$$r = \frac{\frac{273}{38} - [1.368 \cdot (-0.474)]}{2.41 \cdot 3.78} \cong 0.716.$$

The following formulae are employed to calculate linear correlated dependencies:

a) for a dependence of the mean value $\bar{y}$ upon x

$$y-\bar{y}=b_y(x-\bar{x}); \tag{16}$$

b) for a dependence of the mean value $\bar{x}$ upon y

$$x-\bar{x}=b_x(y-\bar{y}). \tag{17}$$

In these equations b_y and b_x represent angular coefficients of straight lines drawn to the axis of coordinates and are computed according to the following formulae:

$$b_x=\frac{r\cdot\delta_x}{\delta_y}, \tag{18}$$

$$b_y=\frac{r\cdot\delta_y}{\delta_x}, \tag{19}$$

where r=the correlation coefficient equal to 0.716 in the given example;

δ_x=root-mean-square deviation of the variable x;

δ_y=root-mean-square deviation of the variable y.

It should be particularly stressed that in computing b_x, b_y, δ_x and δ_y, the values found from the correlation table in conventional units for $\bar{x}$, $\bar{y}$, δ_x, and δ_y should be converted so as to acquire their true values.

The true value δ_x is equal to its conventional value (in this case 3.78) miltiplied by the capacity of the interval (k) of values x (in this case $k=10$).

$$\delta_x=3.78\cdot 10 \ =37.8$$

Similarly, δ_y is equal to its conventional value (2.4) multiplied by the capacity of the interval, which in this case is also equal to 10.

$$\delta_y=2.41\cdot 10=24.1$$

The true mean value x is equal to the mean value x_0 of the interval of values x, which latter is equal to zero (in this case the zero interval of the values for x lies within a range of from 50 to 60, with the mean value equal to 55) plus the product of the capacity of the interval (10 cm.) by the value v_1.

$$\bar{x}=x_0+kv_1 \ =55+10\times 1.368=68.68 \tag{20}$$

Similarly, the mean value $\bar{y}$ is equal to the mean value y_0 of the interval of the y_1 values accepted as zero (in this case equal to the zero interval of the values for y which lie within a range of from 40 to 50 and at a mean value equal

to 45) plus the product of the capacity of the interval (10 cm.) by the value v_2.

$$\bar{y}=y_0+kv_2=45+10\cdot(-0.474)=40.26 \qquad (21)$$

Hence

$$b_x=\frac{0.716\cdot 37.8}{24.1}=1.11;$$

$$b_y=\frac{0.716\ 24.1}{37.8}=0.456.$$

Consequently, the desired linear correlated dependencies will be as follows:

$$x_y=66.68=1.11\ (y-40.26) \text{ or } x_y=2.24+1.11y;$$
$$y_x=40.26=0.456\ (x-66.68) \text{ or } y_x=8.59+0.46\ x.$$

In the forecasting of ground water levels, only the second of these two dependencies will be of interest to us, since it will enable us to determine the mean value of the level of ground waters for a forthcoming month (y_x) depending upon its position in the preceding month (x_y).

When compiling correlation tables, particular attention should be paid to selecting the interval, or, as it is expressed in mathematical statistics, the capacity of the interval. In our example this capacity was equal to 10 cm. It must be remembered that the greater the capacity of the interval, the easier will subsequent calculations be, but the accuracy of the correlated dependency will be proportionally lower. It is desirable, but not obligatory, to choose the same numerical capacity of intervals both for the values y and x.

Let us now check the method's accuracy: assume that in June the level of ground waters was at a height of 80 cm. Then according to the obtained correlated dependency, in July it should be at a height of

$$y_x=8.59+0.46x\approx 35.4 \text{ cm}.$$

During the following month, possible deviations of the calculated mean values of ground water level from actual deviations will be equal to

$$\Delta y=\delta_y\sqrt{1-r^2} \qquad (22)$$

and for the dependence of x upon y

$$\Delta x=\delta_x\sqrt{1-r^2}. \qquad (23)$$

In this connection it should be noted that a single value of Δy or Δx will ensure a 68% probability or reliability of the value of y obtained in accordance with the correlated dependency; in other words, 32% of the levels of ground waters might have other values from that of $y \pm \Delta y$; a double value of Δy ensures a 95% probability, i. e., the levels of ground waters will be within the limits of $y \pm \Delta y$; and finally, a triple value will make reliability certain in 99 cases out of hundred.

In our example Δy is equal to

$$\Delta y = \delta_y \sqrt{1 - r^2} = 24.1 \sqrt{1 - (0.716)^2} = 24.1 \cdot 0.69 \cong 16 \text{ cm.}$$

Hence the level of ground waters will be found within the limits of 35.4 ± 16, that is, from 51.4 to 19.4 cm. in 68 cases out of a hundred. Accuracy of calculations based on the correlated dependency will be considerably increased if the forecast will be given not only for one, but for a group of wells according to the following formula:

$$\Delta n = \frac{\Delta y}{\sqrt{n}},$$

where n—number of wells.

For example, if there are 25 wells the value of a possible deviation will be equal to

$$\Delta n = \frac{16}{\sqrt{25}} \cong 3 \text{ cm.}$$

Hence the level of ground waters, found by us to have a 68% probability and equal to 35.4 cm. for 25 wells will actually be within the limits of 35.4 ± 3 cm.; those with a probability of 95% will be within the limits of 35.4 ± 6 cm.; and those with a 99% probability will be within the limits of 35.4 ± 9 cm.

We have already discussed linear correlated dependencies. However, more complex curvilinear, and particularly exponential dependencies are often encountered in practice. In such cases an exponential dependency may be transformed into the linear type by the finding of corresponding logarithms (logarithms of numbers being used in all the above-stated operations) and, in the end, by reversing the computations back to numbers. There are also other methods of

reducing the dependencies under survey into linear, as the following example show (through the finding of logarithms):

1. The curve in the form of $y=ax^b$ may be used in a linear dependency between lg y and lg x.

2. The curve in the form $y=ae^{bx}$ may be used in a linear dependency between lg y and x, since ln $y=$ln $a+bx$.

3. The curve in the form of $y=a+bx^a$ is suitable for a linear dependency between y and x^a.

4. The curve in the form of $y=\frac{1}{a+bx}$ may be used in a linear relation between $\frac{1}{y}$ and x.

5. The curve in the form of $y=\frac{x}{a+bx}$ is suitable for a linear dependence between $\frac{1}{y}$ and $\frac{1}{x}$, since $y=\frac{x}{a+bx}$; $\frac{x}{y}=a+bx$ and $\frac{x}{y}=a+bx$; $\frac{1}{y}=b+a\frac{1}{x}$, etc.

When dealing with curvilinear dependencies the first question to arise is the selection of the proper type of curve for any given formula. For this purpose a curve drawn on the basis of actual data and showing the relation between the values under survey, should be compared with curves corresponding to definite formulae and then the most suitable selected (by similarity).

Then the points representing the values of the selected formula reduced to the linear form are plotted on the diagram in the manner already indicated. For example, a curve in the form of $y=ax^b$ is drawn according to the values lg y and lg x, while the curve in the form of $y=\frac{1}{a+bx}$ is drawn according to the values $\frac{1}{y}$ and x. If the diagram should show that the relation between lg y and lg x, in the first case, and between $\frac{1}{y}$ and x in the second is actually close to a linear dependency, then a final selection of the formulae is made with subsequent compilation of the correlation table and all other corresponding operations. All these operations in determining correlated dependencies remain the same, but the following points should be borne in mind:

a) the capacity of the interval in logarithms should be taken equal to 0.1 of the logarithm. Furthermore, it may become necessary to employ negative logarithmic intervals for numbers smaller than 1;

b) as a result of computations a logarithmic or a semi-logarithmic correlation coefficient may be obtained;

c) when using a semi-logarithmic correlation table for the determination of relations both between lg y and x, the mean values of y in which we are interested will be somewhat underestimated, because computations are actually made not on the basis of arithmetical means, but on those of geometrical means. In the case of logarithmical correlation tables (relations between lg y and lg x) this is of no consequence.

TO THE READER

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